

Aberystwyth University

Greenhouse gas emissions from natural ecosystems and agricultural lands in sub-Saharan Africa

Kim, Dong-Gill; Thomas, Andrew; Pelster, David; Rosenstock, Todd S.; Sanz-Cobena, Alberto

Published in:
Biogeosciences

DOI:
[10.5194/bg-13-4789-2016](https://doi.org/10.5194/bg-13-4789-2016)

Publication date:
2016

Citation for published version (APA):

Kim, D-G., Thomas, A., Pelster, D., Rosenstock, T. S., & Sanz-Cobena, A. (2016). Greenhouse gas emissions from natural ecosystems and agricultural lands in sub-Saharan Africa: synthesis of available data and suggestions for further research. *Biogeosciences*, 13(16), 4789-4809. <https://doi.org/10.5194/bg-13-4789-2016>

Document License CC BY

General rights

Copyright and moral rights for the publications made accessible in the Aberystwyth Research Portal (the Institutional Repository) are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the Aberystwyth Research Portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the Aberystwyth Research Portal

Take down policy

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

tel: +44 1970 62 2400
email: is@aber.ac.uk



Greenhouse gas emissions from natural ecosystems and agricultural lands in sub-Saharan Africa: synthesis of available data and suggestions for further research

Dong-Gill Kim¹, Andrew D. Thomas², David Pelster³, Todd S. Rosenstock⁴, and Alberto Sanz-Cobena⁵

¹Wondo Genet College of Forestry and Natural Resources, Hawassa University, P.O. Box 128, Shashemene, Ethiopia

²Department of Geography and Earth Sciences, Aberystwyth University, Aberystwyth SY23 3DB, UK

³International Livestock Research Institute, P.O. Box 30709, Nairobi, Kenya

⁴World Agroforestry Centre (ICRAF), P.O. Box 30677-00100, United Nations Avenue, Nairobi, Kenya

⁵Technical University of Madrid, School of Agriculture, Avd. Complutense s/n, 28040 Madrid, Spain

Correspondence to: Dong-Gill Kim (donggillkim@gmail.com)

Received: 6 September 2015 – Published in Biogeosciences Discuss.: 9 October 2015

Revised: 23 July 2016 – Accepted: 3 August 2016 – Published: 29 August 2016

Abstract. This paper summarizes currently available data on greenhouse gas (GHG) emissions from African natural ecosystems and agricultural lands. The available data are used to synthesize current understanding of the drivers of change in GHG emissions, outline the knowledge gaps, and suggest future directions and strategies for GHG emission research. GHG emission data were collected from 75 studies conducted in 22 countries ($n = 244$) in sub-Saharan Africa (SSA). Carbon dioxide (CO_2) emissions were by far the largest contributor to GHG emissions and global warming potential (GWP) in SSA natural terrestrial systems. CO_2 emissions ranged from 3.3 to 57.0 $\text{Mg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$, methane (CH_4) emissions ranged from -4.8 to 3.5 $\text{kg ha}^{-1} \text{ yr}^{-1}$ (-0.16 to 0.12 Mg CO_2 equivalent (eq.) $\text{ha}^{-1} \text{ yr}^{-1}$), and nitrous oxide (N_2O) emissions ranged from -0.1 to 13.7 $\text{kg ha}^{-1} \text{ yr}^{-1}$ (-0.03 to 4.1 Mg CO_2 eq. $\text{ha}^{-1} \text{ yr}^{-1}$). Soil physical and chemical properties, rewetting, vegetation type, forest management, and land-use changes were all found to be important factors affecting soil GHG emissions from natural terrestrial systems. In aquatic systems, CO_2 was the largest contributor to total GHG emissions, ranging from 5.7 to 232.0 $\text{Mg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$, followed by -26.3 to 2741.9 $\text{kg CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$ (-0.89 to 93.2 Mg CO_2 eq. $\text{ha}^{-1} \text{ yr}^{-1}$) and 0.2 to 3.5 $\text{kg N}_2\text{O ha}^{-1} \text{ yr}^{-1}$ (0.06 to 1.0 Mg CO_2 eq. $\text{ha}^{-1} \text{ yr}^{-1}$). Rates of all GHG emissions from aquatic systems were affected by type, location,

hydrological characteristics, and water quality. In croplands, soil GHG emissions were also dominated by CO_2 , ranging from 1.7 to 141.2 $\text{Mg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$, with -1.3 to 66.7 $\text{kg CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$ (-0.04 to 2.3 Mg CO_2 eq. $\text{ha}^{-1} \text{ yr}^{-1}$) and 0.05 to 112.0 $\text{kg N}_2\text{O ha}^{-1} \text{ yr}^{-1}$ (0.015 to 33.4 Mg CO_2 eq. $\text{ha}^{-1} \text{ yr}^{-1}$). N_2O emission factors (EFs) ranged from 0.01 to 4.1 %. Incorporation of crop residues or manure with inorganic fertilizers invariably resulted in significant changes in GHG emissions, but results were inconsistent as the magnitude and direction of changes were differed by gas. Soil GHG emissions from vegetable gardens ranged from 73.3 to 132.0 $\text{Mg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ and 53.4 to 177.6 $\text{kg N}_2\text{O ha}^{-1} \text{ yr}^{-1}$ (15.9 to 52.9 Mg CO_2 eq. $\text{ha}^{-1} \text{ yr}^{-1}$) and N_2O EFs ranged from 3 to 4 %. Soil CO_2 and N_2O emissions from agroforestry were 38.6 $\text{Mg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ and 0.2 to 26.7 $\text{kg N}_2\text{O ha}^{-1} \text{ yr}^{-1}$ (0.06 to 8.0 Mg CO_2 eq. $\text{ha}^{-1} \text{ yr}^{-1}$), respectively. Improving fallow with nitrogen (N)-fixing trees led to increased CO_2 and N_2O emissions compared to conventional croplands. The type and quality of plant residue in the fallow is an important control on how CO_2 and N_2O emissions are affected. Throughout agricultural lands, N_2O emissions slowly increased with N inputs below 150 $\text{kg N ha}^{-1} \text{ yr}^{-1}$ and increased exponentially with N application rates up to 300 $\text{kg N ha}^{-1} \text{ yr}^{-1}$. The lowest yield-scaled N_2O emissions were reported with N application rates ranging between 100 and 150 kg N ha^{-1} . Overall, total CO_2 eq. emissions

from SSA natural ecosystems and agricultural lands were $56.9 \pm 12.7 \times 10^9$ Mg CO₂ eq. yr⁻¹ with natural ecosystems and agricultural lands contributing 76.3 and 23.7 %, respectively. Additional GHG emission measurements are urgently required to reduce uncertainty on annual GHG emissions from the different land uses and identify major control factors and mitigation options for low-emission development. A common strategy for addressing this data gap may include identifying priorities for data acquisition, utilizing appropriate technologies, and involving international networks and collaboration.

1 Introduction

Global greenhouse gas (GHG) emissions were estimated to be 49×10^9 Mg CO₂ eq. in 2010 (IPCC, 2014), with approximately 21.2–24 % (10.3 – 12×10^9 Mg CO₂ eq.) of emissions originating from soils in agricultural, forestry and other land use (AFOLU; Tubiello et al., 2015; IPCC, 2014). Annual non-CO₂ GHG emissions (primarily CH₄ and N₂O) from agriculture were estimated to be 5.2 – 5.8×10^9 Mg CO₂ eq. yr⁻¹ in 2010 (FAOSTAT, 2015; Tubiello et al., 2013), with approximately 4.3 – 5.5×10^9 Mg CO₂ eq. yr⁻¹ attributable to land-use change (IPCC, 2014).

Greenhouse gas fluxes in Africa play an important role in the global GHG budget (Thompson et al., 2014; Hickman et al., 2014; Valentini et al., 2014; Ciais et al., 2011; Bombelli et al., 2009). For example, CO₂ eq. emissions from 12 river channels in SSA and wetlands of the Congo River were 3.3×10^9 Mg CO₂ eq. per year, equivalent to ca. 25 % of the global terrestrial and ocean carbon sink (Borges et al., 2015). Nitrous oxide emissions in SSA contribute between 6 and 19 % of the global total, and changes in soil N₂O fluxes in SSA drive large interannual variations in tropical and subtropical N₂O sources (Thompson et al., 2014; Hickman et al., 2011). Use of synthetic fertilizers such as urea has increased in the last four decades, as has the number of livestock (and their manure and urine products) in Africa (Bouwman et al., 2009, 2013). The increasing trend in N application rates is expected to cause a 2-fold increase in agricultural N₂O emissions in the continent by 2050 (from 2000; Hickman et al., 2011). In the case of CH₄ emissions, there are important differences between ecosystems. Tropical humid forest, wetlands, rice paddy fields, and termite mounds are likely sources of CH₄, while seasonally dry forests and savannahs are typically CH₄ sinks (Valentini et al., 2014).

Interpretation of GHG emissions from soils and terrestrial water bodies is complex because of the multiple, sometimes competing, biological, chemical, and physical processes affecting fluxes. Spatial and temporal variability in GHG fluxes is also high and challenging to capture with direct measurement. This in turn makes reliable annual GHG flux estimates

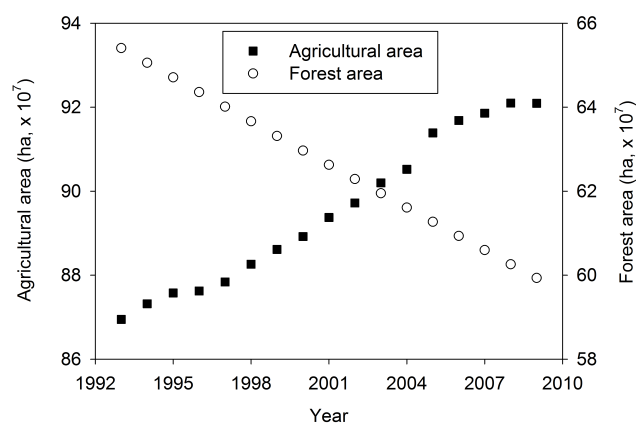


Figure 1. Change in areas of agricultural land and forest in Africa. Data source: FAOSTAT, <http://faostat.fao.org/site/377/default.aspx#ancor>.

from different soils, land uses, and regions quite rare in SSA. Net soil CO₂ flux is largely a product of autotrophic respiration derived from plant roots and heterotrophic respiration of soil organic matter (Raich and Schlesinger, 1992). Soil CO₂ flux provides an integrated result of biological CO₂ production throughout the soil column, changes in soil CO₂ diffusivity in the soil profile, and in some areas geological processes (Raich and Schlesinger, 1992). Net CH₄ flux is the result of the balance between methanogenesis (microbial production under anaerobic conditions) and methanotrophy (microbial consumption) (Dutaur and Verchot, 2007). Methanogenesis occurs via the anaerobic degradation of organic matter by methanogenic archaea within the archaeal phylum *Euryarchaeota* (Thauer, 1988). Methanotrophy occurs by methanotrophs metabolizing CH₄ as their source of carbon and energy (Hanson and Hanson, 1996). Soil N₂O is produced through three main processes such as nitrification (Kowalchuk and Stephen, 2001), denitrification (Knowles, 1982), and nitrifier denitrification (Wrage et al., 2001). Identifying controlling factors and their effects on all GHGs is therefore complex and challenging but a pre-requisite to enhancing our understanding of efflux mechanisms and accurate quantification of GHG emissions. Environmental factors such as soil properties (e.g., soil type, carbon, and nutrients; Pelster et al., 2012), climate characteristics (e.g., temperature, rainfall, drought; Dijkstra et al., 2012), and vegetation type (e.g., crop or forest types; Masaka et al., 2014) also affect GHG fluxes. Management practices can also play important roles in controlling GHG fluxes. The controlling management practices include land-use change (Kim and Kirschbaum, 2015), logging (Yashiro et al., 2008), changing water discharge (Wang et al., 2013), soil compaction (Ball et al., 1999), tillage (Sheehy et al., 2013), removal of crop residues (Jin et al., 2014), and N input (whether organic or inorganic; Hickman et al., 2015).

Our current understanding of GHG emissions in SSA is particularly limited when compared to the potential the continent has as both a GHG sink and a source. This lack of data on GHG emissions from African natural and agricultural lands and the lack of a comprehensive analysis of existing data (i.e., type of emission drivers: natural factors or anthropic ones) hinder the progress of our understanding of GHG emissions on the continent (Hickman et al., 2014; Valentini et al., 2014; Ciais et al., 2011; Bombelli et al., 2009). In order to identify mitigation measures and other climate-smart interventions for the region, it is important to quantify baseline GHG emissions, as well as understand the impacts of different land-use management strategies on GHG emissions (e.g., Palm et al., 2010). In this study our objectives are to synthesize currently available data on GHG emissions in natural ecosystems and agricultural lands in SSA, create an inventory of information from studies on emissions, and select priority topics for future GHG emission studies in natural ecosystems and agricultural lands in SSA.

2 Methodology

2.1 Data collection and analyses

Data were acquired by searching existing peer-reviewed literature using the names of the sub-Saharan countries and the GHGs (i.e., CO₂, CH₄, N₂O) as search terms (using Web of Science and Google Scholar; 1960–2015). These criteria yielded 310 peer-reviewed papers. To produce the quantitative summary of GHG emissions, we selected studies that reported in situ annual GHG emissions or those that provided enough information to estimate annual GHG emissions through unit conversion and/or extrapolation of given data. Data from 75 studies, conducted in 22 countries ($n = 244$) in SSA, were used and were further categorized as GHG emission in natural ecosystems ($n = 117$; Supplement Table S1) and agricultural lands ($n = 127$; Table S2; Fig. 2). The category of GHG emissions in natural ecosystems were further divided into emissions from natural terrestrial systems (forest/plantation/woodland ($n = 55$), savannah/grassland ($n = 31$), termite mounds ($n = 5$), and salt pans ($n = 1$)) and aquatic systems (streams/rivers ($n = 14$), wetlands/floodplains/lagoons/reservoirs/lakes ($n = 11$)) (Table 1). Greenhouse gas emissions in agricultural lands were subdivided into emissions from cropland ($n = 105$), rice paddies ($n = 1$), vegetable gardens ($n = 5$), and agroforestry ($n = 16$; Table 1). Across all categories there were 174 CO₂, 201 CH₄, and 184 N₂O emissions measurements. To allow comparison between different GHG emissions CH₄ and N₂O emissions were converted to CO₂ eq. assuming a 100-year global warming potential and values of 34 and 298 kg CO₂ eq. for CH₄ and N₂O, respectively (IPCC, 2013). Where N₂O emission studies included experimental data from control plots with no N fertilizer additions (i.e., for

background N₂O emissions), and from plots with different levels of applied N, a N₂O emission factor (EF) was calculated following the IPCC (2006) Tier I methodology as follows:

$$\text{N}_2\text{O EF}(\%) = \frac{\text{N}_2\text{O emission}_{\text{N treatment}} - \text{N}_2\text{O emission}_{\text{control}}}{\text{N}_{\text{input}}} \times 100, \quad (1)$$

where N₂O EF (%) is N₂O emission factor, N₂O emission_{N treatment} is N₂O emission in N input, N₂O emission_{control} is control treatments with no N fertilizer additions, and N_{input} is the amount of added N.

It should be noted that our data compilation includes a wide variety of studies that were conducted under diverse biophysical conditions using a range of methodologies for quantifying GHG emissions (e.g., different sampling protocols, chamber design, and emission rate calculations), soil properties, and climatic factors. Therefore, the overall figures on GHG emissions shown are based on results achieved by different measurement techniques with inherent and contrasting sources of error. To assess data quality of the cited studies we used the criteria (ranked from “very poor” to “very good”) suggested by Rochette and Eriksen-Hamel (2008). These were originally intended for chamber N₂O measurements but are equally applicable to field-based CO₂ and CH₄ chamber measurements. We went through the methods of the papers used in the study (only those for terrestrial emissions, since these criteria are not applicable for aquatic systems) where there was sufficient detail in the methods section. We categorized the studies as three different groups: the methods are (1) poor to very poor, (2) marginal and (3) good. Studies that were ranked “poor” on 3 or more criteria or “very poor” on 2 or more criteria were categorized as such because the methods were poor to very poor. In addition, we took into account the importance of sampling frequency (Barton et al., 2015) and sampling periods. Studies estimating annual GHG emissions with a sampling frequency lower than biweekly (i.e., less than two times per month) and sampling periods of less than 6 months (i.e., covering both rainy and dry seasons) were also categorized as poor to very poor. Studies that were ranked as “poor” on two criteria, or “very poor” on one criterion, or with insufficient details on the methods were ranked as marginal. The good studies were those with only one “poor” ranking, sufficient detail, and a sampling frequency of every 2 weeks or more frequent.

2.2 Statistical analyses

To determine the relationship between annual soil CO₂ emissions and edaphic and climatic factors (e.g., soil pH, soil bulk density, soil organic carbon (SOC), total N, and annual average air temperature and rainfall) in SSA natural terrestrial systems and agricultural lands, we used a Pearson correlation analysis. The compiled datasets were used to examine the best model fit selection for N₂O emissions and yield-scaled N₂O emissions as a function of the respective N input levels. Different data fitting models (linear, nonlinear,

Table 1. Summary of greenhouse gas carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), emissions and CO₂ equivalents (CO₂ eq.) in natural ecosystems and agricultural lands in sub-Saharan African countries. Mean \pm standard error (number of data) are shown.

Type	Area (Mha)	CO ₂ emission	CH ₄ emission	N ₂ O emission	N ₂ O emission factor	CO ₂ eq. emission	Total CO ₂ eq. emission
		Mg CO ₂ ha ⁻¹ yr ⁻¹	kg CH ₄ ha ⁻¹ yr ⁻¹	kg N ₂ O ha ⁻¹ yr ⁻¹	%	Mg CO ₂ eq. ha ⁻¹ yr ⁻¹	$\times 10^3$ Mg CO ₂ eq. yr ⁻¹
Forest/plantation/woodland	740.6 ^a	32.0 \pm 5.0 (34)	-1.5 \pm 0.6 (15)	4.2 \pm 1.5 (10)	d	34.0 \pm 5.7	25.2 \pm 4.2
Savannah/grassland	638.9 ^a	15.5 \pm 3.8 (11)	0.5 \pm 0.4 (18)	0.6 \pm 0.1 (6)	d	15.8 \pm 3.8	10.1 \pm 2.4
Stream/river	28.2 ^a	78.1 \pm 13.2 (27)	436.3 \pm 133.8 (24)	1.6 \pm 0.3 (17)	d	93.4 \pm 17.9	2.8 \pm 1.0
Wetlands/floodplains/lagoons/reservoir	43.8 ^a	96.6 \pm 31.0 (7)	950.4 \pm 350.4 (5)	2.0 \pm 1.5 (2)	d	121.3 \pm 39.7	5.3 \pm 1.7
Termite mounds	0.97 ^b	11.6 \pm 6.2 (3)	2.3 \pm 1.1 (3)	0.01 (1)	d	11.7 \pm 6.3	0.01 \pm 0.01
Salt pan	d	0.7 (1)	d	d	d	d	d
Total natural ecosystems ^h	1452.5	27.6 \pm 2.9 ^c	43.0 \pm 5.8 ^c	2.5 \pm 0.4 ^c	d	29.9 \pm 22.5 ^c	43.4 \pm 9.3 (76.3 %) ^g
Cropland	468.7 ^a	23.4 \pm 5.1 (45)	19.3 \pm 4.2 (26)	4.0 \pm 1.5 (83)	0.5 \pm 0.2 (24)	26.1 \pm 6.0	12.2 \pm 2.8
Rice field	10.5 ^c	6.5 (1)	30.5 (1)	0.19 (1)	d	7.3	1.3 \pm 0.6
Vegetable gardens	d	96.4 \pm 10.2 (5)	d	120.1 \pm 26.1 (5)	3.5 \pm 0.5 (2)	d	d
Agroforestry	190 ^f	38.6 (1)	d	4.7 \pm 2.2 (15)	d	d	d
Total agricultural lands ⁱ	479.2	23.0 \pm 8.5 ^c	19.5 \pm 5.6 ^c	4.5 \pm 2.2 ^c	d	25.6 \pm 12.4 ^c	13.5 \pm 3.4 (23.7 %) ^g
Total natural ecosystems and agricultural lands ^j	1931.7						56.9 \pm 12.7

^a GlobCover 2009. ^b 0.07 % of savannah and rainforest (Brümmer et al., 2009). ^c FAO STAT (<http://faostat3.fao.org/home/E>), year 2012. ^d No data available. ^e Area-weighted average. ^f Zomer et al. (2009). ^g Contribution to CO₂ eq. emission in total natural and agricultural lands. ^h Except salt pan. ⁱ Except vegetable gardens and agroforestry. ^j Except salt pan, vegetable gardens, and agroforestry.

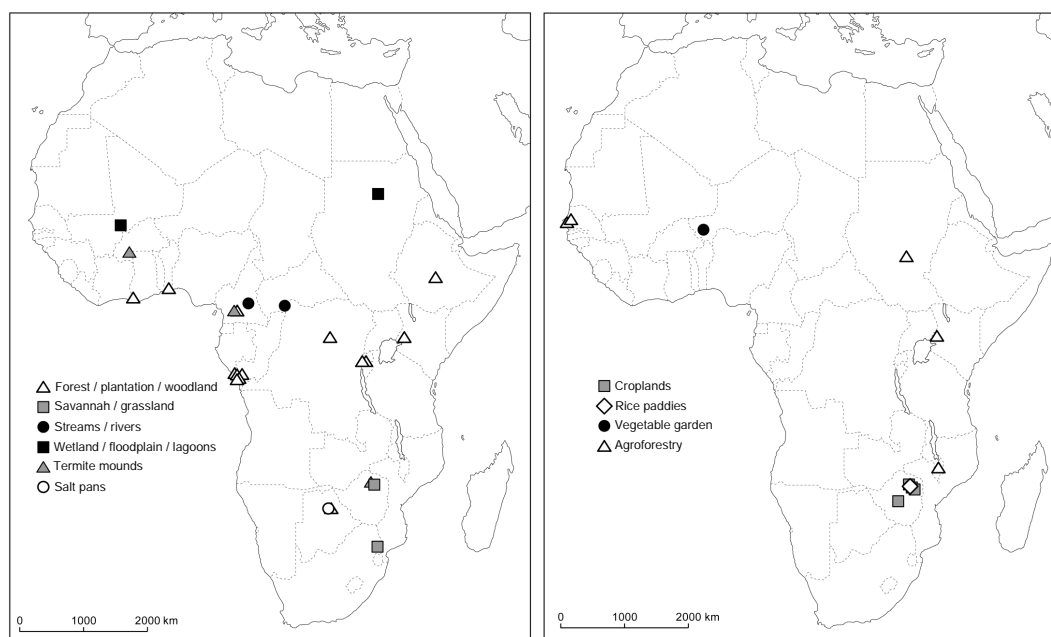


Figure 2. Maps showing study sites of CO₂, CH₄, and N₂O fluxes in natural ecosystems (left) and agricultural lands (right) in sub-Saharan Africa.

natural log, logarithm, and sigmoidal) were tested for each dataset. The regression models were checked for violation of assumptions of normal distribution (Shapiro–Wilk test), homoscedasticity (Breusch–Pagan test), and constant variance (Durbin–Watson statistic; Motulsky and Christopoulos, 2004). Separate *t* tests were used to assess significance of regression coefficients and intercepts in the fitted parametric models. Adjusted coefficients of determination (adjusted *R*²) of fitted parametric models were used as criteria for model selection: the model with the highest adjusted *R*² was selected. Statistical significance was considered at the critical level of 5 %. Statistical analyses were conducted using SAS[®]

version 9.2 (SAS Institute, Cary, NC, USA) and SigmaPlot[®] version 11.0 (Systat Software Inc., San Jose, CA, USA).

3 Results and discussion

3.1 Summary of greenhouse gas emissions

3.1.1 CO₂ emissions

Carbon dioxide emissions ranged from 3.3 to 130.9 Mg CO₂ ha⁻¹ yr⁻¹ in natural terrestrial systems and from -11.9 to 232.0 Mg CO₂ ha⁻¹ yr⁻¹

in aquatic systems. The area-weighted average was $27.6 \pm 17.2 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ (Tables 1 and S1). Aquatic systems such as water bodies or water submerged lands were the largest source of CO_2 , followed by forest, savannah, termite mounds, and salt pans (Table 1). Soil CO_2 emissions in agricultural lands were similar to emissions from natural lands and ranged from 6.5 to $141.2 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ with an area-weighted average of $23.0 \pm 8.5 \text{ Mg CO}_2 \text{ ha}^{-1} \text{ yr}^{-1}$ (Tables 1 and S2). Vegetable gardens were the largest sources of CO_2 emission largely due to the excessive C inputs. However, this conclusion was based on two studies that used photoacoustic spectroscopy, which has been found have mixed results due to cross sensitivities between the various GHG and water vapor (Rosenstock et al., 2013; Iqbal et al., 2013), suggesting that vegetable gardens require further study. The next largest sources of emissions were agroforestry, cropland, and then rice production systems (Tables 1 and S2).

Observed annual soil CO_2 emissions in African natural terrestrial systems and agricultural lands showed significant correlations with annual mean air temperature ($r = -0.322$, $P = 0.01$), annual rainfall ($r = 0.518$, $P < 0.001$), SOC ($r = 0.626$, $P < 0.001$), and soil total N content ($r = 0.849$, $P < 0.001$; Table 2). The negative relationship between annual soil CO_2 emissions and annual mean air temperature was unexpected since positive correlations between soil CO_2 flux and temperature are well established (e.g., Bond-Lamberty and Thomson, 2010). We speculate that the generally high temperatures, and poor quality, of many African soils mean that air temperature increases frequently result in vegetation stress and/or soil aridity, hindering root and soil microbial activities (root and microbial respiration) and subsequent soil CO_2 flux (e.g., Thomas et al., 2011). This would account for the negative relationship observed between annual mean air temperature and annual soil CO_2 emissions, but this remains a largely untested hypothesis that deserves further exploration.

Many of these estimates are based on short-term, infrequent, or poor-quality sampling (Table S1), suggesting that the uncertainties are likely much greater than the provided standard error. This is not meant as a critique of these studies, as many of them were specifically designed to answer specific research questions about the effects of various factors on emission rates rather than determining the cumulative annual emissions. However, given the lack of other data, these still provide the “best guess” for cumulative emissions.

3.1.2 CH_4 emissions

Forest/plantation/woodland were sinks of CH_4 ($-1.5 \pm 0.6 \text{ kg CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$) and savannah/grassland, croplands, termite mounds, and rice fields were low to moderate CH_4 sources ($0.5\text{--}30.5 \text{ kg CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$). Stream/river and wetland/floodplain/lagoon/reservoir were high CH_4 sources ($766.0\text{--}950.4 \text{ kg CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$; Tables 1

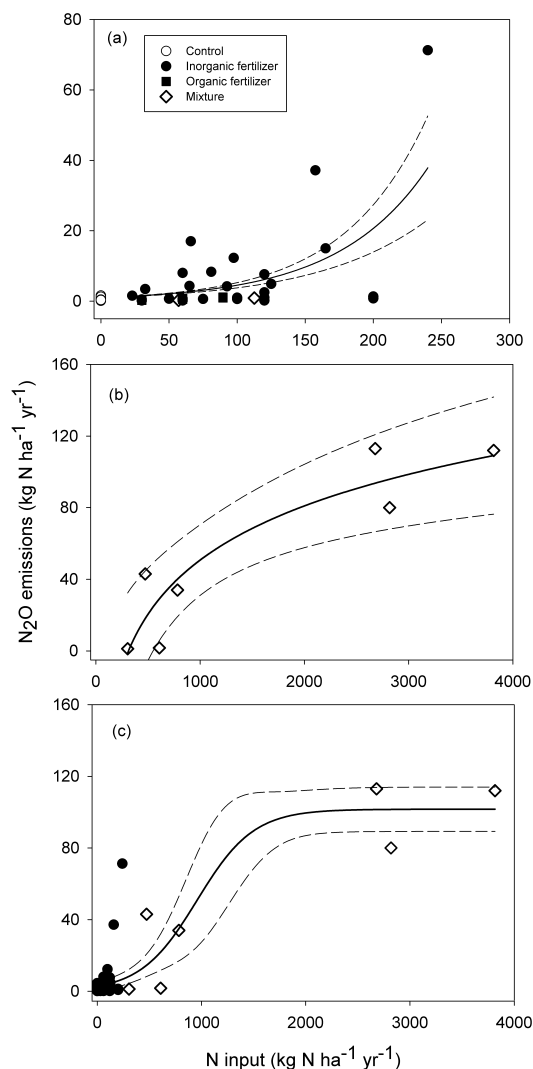


Figure 3. Relationship between nitrogen (N) input and nitrous oxide (N_2O) emissions observed in Africa. N input ranged from 0 to 300 (a), 300 to 4000 (b), and 0 to 4000 $\text{kg N ha}^{-1} \text{ yr}^{-1}$ (c). The dashed lines indicate 95 % confidence intervals. “Control” indicates no fertilizer application, Organic fertilizer is manure; “Inorganic fertilizer” includes NPK, ammonium nitrate, and urea fertilizers; and “Mixture” indicates mixed application of organic and inorganic fertilizers.

and S1). The area-weighted averages of CH_4 emissions from natural and agricultural lands were 43.0 ± 5.8 and $19.5 \pm 5.6 \text{ kg CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$, respectively. As with studies on CO_2 emissions, many of these studies used only infrequent or poor sampling methodologies (Table S1), and there is a high degree of uncertainty surrounding the estimates.

3.1.3 N_2O emissions and emission factor (EF)

Nitrous oxide emissions in natural ecosystems ranged from -0.1 to $13.7 \text{ kg N}_2\text{O ha}^{-1} \text{ yr}^{-1}$ and the area-weighted aver-

Table 2. Correlation between annual soil CO₂ emissions (Mg CO₂ ha⁻¹ yr⁻¹) and environmental factors in African natural terrestrial systems.

	Annual mean air temperature (°C)	Annual rainfall (mm)	Soil organic carbon (%)	Soil total nitrogen (%)
Correlation coefficient	-0.322	0.518	0.626	0.849
<i>P</i> value	0.01	<0.001	<0.001	<0.001
Number of samples	60	61	31	26

age was 2.5 ± 0.8 kg N₂O ha⁻¹ yr⁻¹ (Tables 1 and S1). Our study reveals that forest, plantation, and woodland were the largest source of N₂O, followed by rivers and wetlands, savannah, and termite mounds in natural ecosystems (Table 1). Soil N₂O emissions in agricultural lands ranged from 0.051 to 177.6 kg N₂O ha⁻¹ yr⁻¹ and the area-weighted average was 4.5 ± 2.2 kg N₂O ha⁻¹ yr⁻¹ (Tables 1 and S2). The largest N₂O source in agricultural lands was vegetable gardens, followed by agroforestry, cropland, and rice fields (Table 1). The N₂O EF was 0.5 ± 0.2 and 3.5 ± 0.5 % for cropland and vegetable gardens, respectively (Tables 1 and S1). The N₂O EF of cropland is lower and the N₂O EF of vegetable gardens is higher than IPCC default N₂O EF (1 %; IPCC, 2006). The number of studies on N₂O emissions in SSA is, however, particularly low ($n = 14$), with some questions regarding the quality of the methods (Table S1) in some of these studies, and there are significant regional gaps leading to large uncertainties in the conclusions that can be currently drawn.

N₂O emissions were significantly affected by N input levels (Fig. 3). N₂O emissions increase slowly up to 150 kg N ha⁻¹ yr⁻¹, after which emissions increase exponentially up to 300 kg N ha⁻¹ yr⁻¹ (Fig. 3a). Consistent with earlier work by Van Groenigen et al. (2010), N inputs of over 300 kg N ha⁻¹ yr⁻¹ resulted in an exponential increase in emission (Fig. 3b), slowing to a steady state with N inputs of 3000 kg N ha⁻¹ yr⁻¹. Overall, the relationship between N input and N₂O emissions shows a sigmoidal pattern (Fig. 3c). The observed relationship is consistent with the proposed hypothetical conceptualization of N₂O emission by Kim et al. (2013), showing a sigmoidal response of N₂O emissions to N input increases. The results suggest that N inputs over 150 kg N ha⁻¹ yr⁻¹ may cause an abnormal increase in N₂O emissions in SSA. The relationship between N input and N₂O emissions shows that the lowest yield-scaled N₂O emissions were reported for N application rates ranging from 100 to 150 kg N ha⁻¹ (Fig. 4). The results are in line with the global meta-analysis of Philiber et al. (2012), who showed that from an N application rate ~ 150 kg N ha⁻¹ the increase in N₂O emissions is not linear but exponential.

3.1.4 CO₂ eq. emission

Carbon dioxide equivalent emission (including CO₂, CH₄, and N₂O) in natural ecosystems ranged from 11.7 to

121.3 Mg CO₂ eq. ha⁻¹ yr⁻¹ and the area-weighted average of CO₂ eq. emissions (excluding salt pans) was 29.9 ± 22.5 Mg CO₂ eq. ha⁻¹ yr⁻¹ (Table 1). Water bodies or water submerged lands such as rivers and wetlands were the largest source of CO₂ eq. emissions, followed by forest/plantation/woodland, savannah/grassland, and termite mounds (Table 1). Carbon dioxide equivalent emissions in agricultural lands ranged from 7.3 to 26.1 Mg CO₂ eq. ha⁻¹ yr⁻¹ and had an area-weighted average of CO₂ eq. emissions (excluding vegetable gardens and agroforestry due to lack of data) of 25.6 ± 12.4 Mg CO₂ eq. ha⁻¹ yr⁻¹ (Table 1).

Total CO₂ eq. emissions in natural lands (excluding salt pans) were $43.4 \pm 9.3 \times 10^9$ Mg CO₂ eq. yr⁻¹, with forest/plantation/woodland the largest source, followed by savannah/grassland, stream/river, wetlands/floodplains/lagoons/reservoir, and termite mounds (Table 1). Total CO₂ eq. emissions in agricultural lands (excluding vegetable gardens and agroforestry) were $13.5 \pm 3.4 \times 10^9$ Mg CO₂ eq. yr⁻¹, with cropland the largest source, followed by rice fields (Table 1). Overall, total CO₂ eq. emissions in natural ecosystems and agricultural lands were $56.9 \pm 12.7 \times 10^9$ Mg CO₂ eq. yr⁻¹ with natural ecosystems and agricultural lands contributing 76.3 and 23.7 %, respectively.

3.1.5 Data quality assessment

For the purposes of this study more than half of the 75 studies cited in the study were categorized as having poor to very poor methods, 19 studies were marginal, and 14 studies were good (Tables S1 and S2). The primary reasons the studies were ranked as poor to very poor were because sampling periods were too short for calculating annual emissions (i.e., less than or only one season of data), sampling frequency was too low (i.e., monthly or less), or a combination of poor methods with the sample collection, primarily insufficient samples per gas collecting chamber and very long chamber deployment times. As mentioned earlier, many of these studies were undertaken to address a specific research question, not determine annual, cumulative emissions. Therefore, the degree of uncertainty around cumulative emissions is likely higher than what is indicated in Table 1.

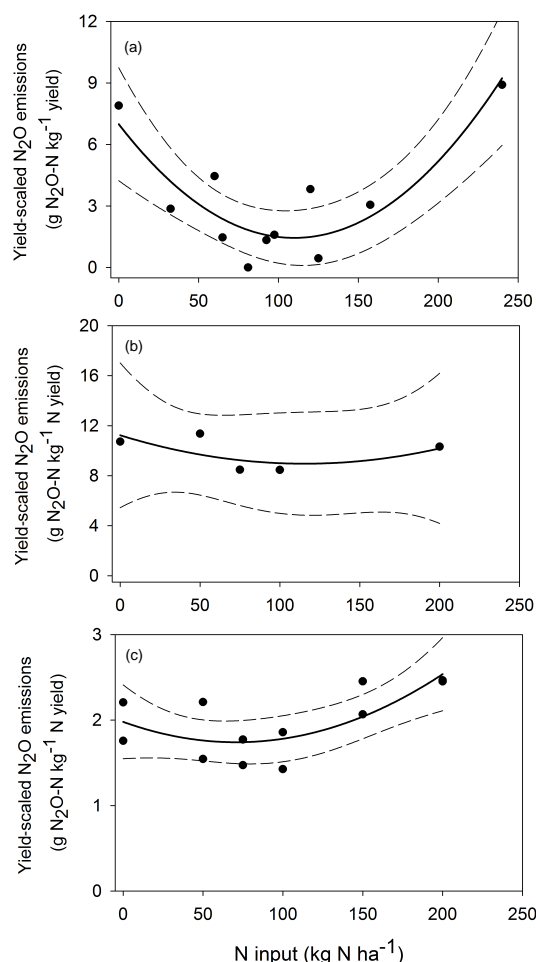


Figure 4. Relationship between nitrogen (N) input and yield scaled nitrous oxide (N_2O) emissions. Grain type: (a) rape (*Brassica napus*) and (b, c) maize (*Zea mays* L.). Data sources: (a) from Nyamadzawo et al. (2014a), (b) from Hickman et al. (2014) and (c) from Hickman et al. (2015). The dashed lines indicate 95 % confidence intervals. Note the different scales across panels.

3.2 Sources and drivers of greenhouse gas emissions in Africa

3.2.1 Greenhouse gas emissions in natural ecosystems

Natural terrestrial systems

A range of factors affect direct emissions of soil CO_2 in SSA natural terrestrial systems such as natural forest, plantation, woodland, savannah, grassland, termite mounds, and salt pans. These factors can be grouped into (i) climatic, (ii) edaphic, (iii) vegetation, and (iv) human interventions via land management (Tables 3 and 4). Data on the effects of these factors on GHG emissions are variable, with some factors much less well understood than others. In almost all cases data are limited to a few studies, and there are areas where there has been no research. This lack of data hinders

our ability to estimate the contribution of African landscapes to global GHG emissions.

Soil CO_2 emissions were related to both soil moisture and temperature in forest systems (Table 3). For example, soil moisture explained about 50 % of the seasonal variability in soil CO_2 efflux in a *Croton macrostachys*, *Podocarpus falcatus*, and *Prunus africana* forest in Ethiopia (Yohannes et al., 2011), as well as much of the seasonal variation in soil CO_2 efflux in a 3-year-old *Eucalyptus* plantation in the Republic of Congo (Epron et al., 2004). Thomas et al. (2011) found that the Q_{10} of soil CO_2 efflux (a measure of the temperature sensitivity of efflux, where a Q_{10} of 2 represents a doubling of efflux given a 10°C increase in temperature) was dependent on soil moisture at sites across the Kalahari in Botswana, ranging from 1.1 in dry soils to 1.5 after a 2 mm rainfall event and 1.95 after a 50 mm event. Similarly, in a Zambian woodland, the main driving factor controlling CO_2 emissions at a seasonal timescale was a combination of soil water content and temperature (Merbold et al., 2011).

Increased GHG emissions following rewetting of dry soil were observed in various regions in SSA (Table 3). Two broad mechanisms responsible for increased soil GHG flux following rewetting of dry soil have been hypothesized: (1) enhanced microbial metabolism by an increase in available substrate due to microbial death and/or destruction of soil aggregates (commonly known as the Birch effect; Birch, 1964), and (2) physical mechanisms influencing gas flux, including infiltration, reduced diffusivity, and gas displacement in the soil (e.g., Kim et al., 2012). Soil CO_2 efflux increased immediately after rainfall in a subtropical palm woodland in northern Botswana; however, the increase was short-lived (Thomas et al., 2014). Large pulses of CO_2 and N_2O , followed by a steady decline, were also observed after the first rainfall event of the wet season in a Kenyan rainforest (Werner et al., 2007). Soil CO_2 efflux was strongly stimulated by addition of rainfall in a South African savannah (Fan et al., 2015; Zepp et al., 1996). In Zimbabwe, the release of N_2O from dryland savannahs was shown to constitute an important pathway of release for N, and emissions were strongly linked to patterns of rainfall (Rees et al., 2006). The results suggest that soil rewetting has a significant impact on GHG emissions in SSA.

Soil physical (e.g., bulk density, porosity, and soil texture) and chemical properties (e.g., pH, C, and N) also affect soil GHG emissions (e.g., Saggarr et al., 2013; Smith, 2010; Snyder et al., 2009; Table 3). Soil CO_2 efflux was positively related to total soil C content in undisturbed miombo woodland in Zambia, although not in an adjacent disturbed woodland (Merbold et al., 2011). In a Kenyan rainforest, CO_2 emissions were negatively correlated with subsoil C and positively correlated with subsoil N concentrations, while N_2O emissions were negatively correlated with clay content and topsoil C : N ratios (Werner et al., 2007). However, soil bulk density and pH were the most influential factors driving spatial variation of in situ N_2O emissions in a tropical high-

Table 3. Summary of environmental factors affecting greenhouse gas (GHG) emissions in land-use/ecosystem type. ◦ indicates GHG affected by environmental factor named.

Land-use/ecosystem type	Environmental factors	GHG			Location (data source)
		CO ₂	N ₂ O	CH ₄	
Forest/plantation/ Woodland	Temperature	•			Zambia (Merbold et al., 2011)
	Soil moisture	•			Ethiopia (Yohannes et al., 2011), Republic of Congo (Epron et al., 2004), Botswana (Thomas et al., 2011), Zambia (Merbold et al., 2011)
	Rewetting of dry soil/rainfall	•	•		Kenya (Werner et al., 2007)
	Soil carbon	•			Zambia (Merbold et al., 2011), Kenya (Werner et al., 2007)
	Soil nitrogen	•			Kenya (Werner et al., 2007)
	Soil C : N		•		Kenya (Werner et al., 2007)
	Soil clay		•		Kenya (Werner et al., 2007)
	Soil bulk density		•		Rwanda (Gharahi Ghehi et al., 2014)
	Soil pH		•		Rwanda (Gharahi Ghehi et al., 2014)
	Vegetation type	•			Republic of Congo (Epron et al., 2013; Caquet et al., 2012; Nouvellon et al., 2012)
Savannah	Rewetting of dry soil/rainfall	•	•		South Africa (Fan et al., 2015; Zepp et al., 1996), Zimbabwe (Rees et al., 2006)
Salt pans	Temperature	•			Botswana (Thomas et al., 2014)
	Flooding	•			Botswana (Thomas et al., 2014)
Streams/rivers/ wetlands/floodplains/ reservoirs/lagoons/lakes	Type	•		•	Congo Basin (Mann et al., 2014), Okavango Delta, Botswana (Gondwe and Masamba, 2014), Lake Kariba, Zambia/Zimbabwe (DelSontro et al., 2011)
	Location	•	•	•	Zambezi River, Zambia/Mozambique (Teodoru et al., 2015), Zimbabwe (Nyamadzawo et al., 2014a)
	Discharge	•		•	Congo River (Wang et al., 2013), Ivory Coast (Koné et al., 2009), Oubangui River, Central African Republic (Bouillon et al., 2012), Lake Kivu (Borges et al., 2011), Zambezi River, Zambia/Mozambique (Teodoru et al., 2015)
	Precipitation	•	•	•	Uganda (Bateganya et al., 2015)
	Water temperature			•	Okavango Delta, Botswana (Gondwe and Masamba, 2014)
	Dissolved inorganic carbon	•			Lake Kivu, East Africa (Borges et al., 2014)

land rainforest in Rwanda (Gharahi Ghehi et al., 2014). Similarly, a laboratory-based experiment using soils from 31 locations in a tropical mountain forest in Rwanda showed that N₂O emissions were negatively correlated with soil pH, and positively correlated with soil moisture, soil C, and soil N (Gharahi Ghehi et al., 2012).

In many temperate systems, vegetation type also affects soil GHG emissions, likely because of differences in litter quality and production rate, amount of below-ground biomass, the structure of root systems, and plant-mediated effects on soil microclimate (e.g., Díaz-Pinés et al., 2014; Masaka et al., 2014; Kim et al., 2010). This is consistent with findings from African systems where annual soil CO₂

Table 4. Summary of the effect of management practices on greenhouse gas (GHG) emissions. + indicates increasing, • indicates no change, and – indicates decreasing.

Land-use/ecosystem type	Management practices	Impact on GHG			Country (data source)
		CO ₂	N ₂ O	CH ₄	
Forest/plantation/ Woodland	Burning	+			Ethiopia (Andersson et al., 2004)
	Thinning	+			Ethiopia (Yohannes et al., 2013)
	Land-use change (cleaning and conversion to croplands)	+	+	+	Zimbabwe (Mapanda et al., 2012; Mapanda et al., 2010)
	Flooding			+	Cameroon (Macdonald et al., 1998); Republic of Congo (Tathy et al., 1992); Mali (Delmas et al., 1991)
Savannah/grassland	Burning	•	•	•	Republic of Congo (Castaldi et al., 2010; Delmas et al., 1991); South Africa (Zepp et al., 1996)
	Land-use change (cleaning and conversion to croplands)	+			¹ Republic of Congo (Nouvellon et al., 2012)
Croplands	Increase in N fertilization rate		+		Kenya (Hickman et al., 2015)
	Type of synthetic fertilizer		•		Madagascar (Rabenarivo et al., 2014)
	Application of plant residues		–		Tanzania (Sugihara et al., 2012); Madagascar (Rabenarivo et al., 2014)
		+	+		Kenya (Kimetu et al., 2007); Ghana (Frimpong et al., 2012)
	Crop residues + N fertilizer		+		⁴ Zimbabwe (Nyamadzawo et al., 2014a, b)
			–		⁵ Zimbabwe, Ghana, and Kenya (Gentile et al., 2008)
	Combination of synthetic and organic fertilizers and organic fertilizers	+	–		⁶ Zimbabwe (Mapanda et al., 2011)
			–		⁷ Mali (Dick et al., 2008)
	Crop type	•			⁸ Uganda (Koerber et al., 2009)
			–		⁹ Zimbabwe (Masaka et al., 2014)
	Introducing N fixing crops in rotations		–		Mali (Dick et al., 2008)
	Direct seeding mulch-based		•		Madagascar (Chapuis-Lardy et al., 2009)
	Hand ploughing after harvesting		•		Madagascar (Chapuis-Lardy et al., 2009)
Vegetable gardens	Intensive grazing	+			Botswana (Thomas, 2012)
	Reduced tillage + mulch, leguminous crop/tree, or N fertilizer	+	+	+; –	Tanzania (Kimaro et al., 2016)
Vegetable gardens	Plastic cover for ruminant manure		–		Niger (Predotova et al., 2010)
	Incorporation of fallow residues		+		Kenya (Baggs et al., 2006; Millar and Baggs, 2004; Millar et al., 2004)
Agroforestry	Improving fallow with N-fixing crops		+		Zimbabwe (Chikowo et al., 2004)
	Cover crops		+		Kenya (Millar et al., 2004)
	N-fixing tree species	+	+		Malawi (Kim, 2012; Makumba et al., 2007); Senegal (Dick et al., 2006)

¹ U + DAP instead U + NPK. ² N₂O study. ³ Low C:N ratio clover residues compared to high C:N ratio barley residues. ⁴ Application of ammonium nitrate with manure to maize (*Zea mays* L.) and winter wheat (*Triticum aestivum* L.) plant residues. ⁵ Plant residues of maize, calliandra, and tithonia + urea. ⁶ Mixed application of composted manure and inorganic fertilizer (AN). ⁷ Manure and urea. ⁸ Lettuces vs. cabbages vs. beans. ⁹ Tomatoes vs. rape.

efflux also varied with vegetation types (Table 3). For example, annual soil CO₂ emissions were significantly lower in N-fixing acacia monocultures than in eucalypt monocultures and mixed-species stands in the Republic of Congo (Epron et al., 2013). The differences were attributed to leaf area index

in another study from savannah grasslands in the Republic of Congo where they found 71 % of seasonal soil CO₂ efflux variability was explained by the quantity of photosynthetically active radiation absorbed by the grass canopy (Caquet et al., 2012). Also in the Republic of Congo, it was found

that in forests, litterfall accounted for most of the age-related trends after the first year of growth, with litter decomposition producing 44 % of soil CO₂ flux in the oldest stand (Nouvelon et al., 2012), suggesting that the amount and quality of litter plays a major role in determining soil CO₂ flux. However, the effect of vegetation type can also interact with soil physical–chemical properties. For example, in Benin, root respiration contributed to 30 % of total soil CO₂ efflux in oil palms when the soil was at field capacity and 80 % when soil was dry (Lamade et al., 1996).

Forest management such as burning, which is a common practice in SSA, and thinning affects GHG emissions (Table 4). The IPCC Tier 1 methodology only calculates the amount of GHG emissions as a percentage of the carbon that is released through the burning; however, it may also increase forest soil GHG emissions once the fire has passed. For example, soil CO₂ efflux immediately increased after burning of woodland in Ethiopia (Andersson et al., 2004); also, 5 days after burning, rainfall resulted in a 2-fold increase in soil CO₂ efflux from the burned plots compared to the unburned plots. In contrast, 12 days after burning soil CO₂ efflux was 21 % lower in the burned plots (Andersson et al., 2004). However, contrasting impacts of fire on soil GHG emission were observed in a savannah/grassland in the Republic of Congo, where fire did not change soil CO₂, CH₄, and N₂O fluxes (Castaldi et al., 2010; Delmas et al., 1991). Similarly, in South Africa, soil CH₄ efflux was not significantly affected by burning (Zepp et al., 1996). In contrast, annual fires decreased soil CH₄ oxidation rates in a Ghanaian savannah (Prieme and Christensen, 1999). These case studies demonstrate that fire impacts are not always consistent and this is likely the result of different fire characteristics (e.g., intensity or frequency), soil type (e.g., Kulmala et al., 2014; Kim et al., 2011), and post-fire weather conditions. Thinning forest cover can also increase soil CO₂ efflux. Yohannes et al. (2013) reported 24 and 14 % increases in soil CO₂ efflux in the first and second years following thinning of a 6-year-old *Cupressus lusitanica* plantation in Ethiopia.

There is a particular paucity of data on sources and sinks of CH₄ in African natural terrestrial systems. In Cameroon, the largest CH₄ oxidation rates were observed from relatively undisturbed near-primary forest sites (−14.7 to −15.2 ng m^{−2} s^{−1}) compared to disturbed forests (−10.5 to 0.6 ng m^{−2} s^{−1}; Macdonald et al., 1998). Savannah and grassland were found to be both a sink and a source of CH₄. In Mali, CH₄ uptake was observed in dry sandy savannah (Delmas et al., 1991), while a savannah in Burkina Faso was found to be both a CH₄ sink and source during the rainy season, although overall it was a net CH₄ source (Brümmer et al., 2009). Termite mounds are known sources of CH₄ and CO₂ (Nyamadzawo et al., 2012; Brümmer et al., 2009). A study in a Burkina Faso savannah found that CH₄ and CO₂ released by termites (*Cubitermes fungifaber*) contributed 8.8 and 0.4 % of total soil CH₄ and CO₂ emissions, respectively (Brümmer et al., 2009). In Cameroon, the mounds of soil-

feeding termites (*Thoracotermes macrothorax* and *Cubitermes fungifaber*) were point sources of CH₄, which at the landscape scale may exceed the general sink capacity of the soil (Macdonald et al., 1998). In Zimbabwe, it was found that *Odontotermes transvaalensis* termite mounds located in dambos (seasonal wetlands) were an important source of GHGs, and emissions varied with catena position for CO₂ and CH₄ (Nyamadzawo et al., 2012).

Compared to the other environments covered in this review there are very few studies from salt pans. Thomas et al. (2014), however, found soil CO₂ efflux increased with temperature and also increased for a few hours after flooding of the surface of the Makgadikgadi salt pan in Botswana. Annual CO₂ emissions in salt pan were estimated as 0.7 Mg CO₂ ha^{−1} yr^{−1} (Thomas et al., 2014).

Aquatic systems

African aquatic systems such as streams, rivers, wetlands, floodplains, reservoirs, lagoons, and lakes can be significant sources of GHG (Tables 1 and S1). Differences in regional setting and hydrology mean that emissions are highly spatially and temporally variable, and when combined with the paucity of studies, it is challenging to identify clear control factors (Table 3).

Studies found SSA aquatic systems can be significant sources of GHG emissions. In Ivory Coast, three out of five lagoons were oversaturated in CO₂ during all seasons and all were CO₂ sources (3.1–16.2 g CO₂ m^{−2} d^{−1}) due to net ecosystem heterotrophy and inputs of riverine CO₂-rich waters (Koné et al., 2009). In the flooded forest zone of the Congo River basin (Republic of Congo) and the Niger River floodplain (Mali), high CH₄ emissions (5.16 × 10²⁰–6.35 × 10²² g CH₄ m^{−2} d^{−1}) were recorded on flooded soils (Tathy et al., 1992; Delmas et al., 1991). In the Nyong River (Cameroon), CO₂ emissions (5.5 kg CO₂ m^{−2} yr^{−1}) were 4 times greater than the flux of dissolved inorganic carbon (Brunet et al., 2009). In the Zambezi River (Zambia), 38 % of the total C in the river is emitted into the atmosphere, mostly as CO₂ (98 %; Teodoru et al., 2015). The source of CH₄ to the atmosphere from Lake Kivu corresponded to ~60 % of the terrestrial sink of atmospheric CH₄ over the lake's catchment (Borges et al., 2011). A recent study of 10 river systems in SSA estimated water–air CO₂, CH₄, and N₂O fluxes to be 8.2 to 66.9 g CO₂ m^{−2} d^{−1}, 0.008 to 0.46 g CH₄ m^{−2} d^{−1}, and 0.09 to 1.23 mg N₂O m^{−2} d^{−1}, respectively (Borges et al., 2015). The authors suggested that lateral inputs of CO₂ from soils, groundwater, and wetlands were the largest contributors of the CO₂ emitted from the river systems (Borges et al., 2015).

The magnitude of GHG emissions from SSA aquatic systems varied with type and location (Table 3). Streams and rivers in savannah regions had higher CO₂ emissions (46.8–56.4 g CO₂ m^{−2} d^{−1}) than swamps (13.7–16.3 g CO₂ m^{−2} d^{−1}) and tropical forest catchments

(37.9–62.9 g CO₂ m⁻² d⁻¹) in the Congo Basin (Mann et al., 2014). The average CH₄ flux in river channels (0.75 g CH₄ m⁻² d⁻¹) was higher than that in floodplains and lagoons (0.41–0.49 g CH₄ m⁻² d⁻¹) in the Okavango Delta (Botswana; Gondwe and Masamba, 2014). Methane emissions from river deltas were substantially higher (~103 mg CH₄ m⁻² d⁻¹) than those from non-river bays (<100 mg CH₄ m⁻² d⁻¹) in Lake Kariba (Zambia/Zimbabwe). Methane fluxes were higher in river deltas (~103 mg CH₄ m⁻² d⁻¹) compared to non-river bays (<100 mg CH₄ m⁻² d⁻¹) in Lake Kariba (Zambia/Zimbabwe; DelSontro et al., 2011). While CO₂ and CH₄ concentrations in the main channel were highest downstream of the floodplains, N₂O concentrations were lowest downstream of the floodplains in the Zambezi River (Zambia and Mozambique; Teodoru et al., 2015). Greenhouse gas emissions from Dambos in Zimbabwe varied with catena position (Nyamadzawo et al., 2014a). Upland dambos were important sources of N₂O and CO₂, and a sink for CH₄, while those in a mid-slope position were a major source of CH₄ but a weak source of CO₂ and N₂O, and those at the bottom were a weak source of all GHGs (Nyamadzawo et al., 2014a).

The concentration and flux of GHGs are strongly linked to hydrological characteristics such as discharge (Table 3), but clear patterns have not yet been identified. Surface CO₂ flux was positively correlated with discharge in the Congo River (Wang et al., 2013), while in Ivory Coast, rivers were often oversaturated with CO₂ and the seasonal variability in partial pressure of CO₂ (*p*CO₂) was due to dilution during the flooding period (Koné et al., 2009). Similarly, CO₂ fluxes show a very pronounced seasonal pattern strongly linked to hydrological conditions in the Oubangui River in the Central African Republic (Bouillon et al., 2012). Although higher CH₄ concentrations were found during low-discharge conditions, N₂O concentrations were lowest during low-discharge conditions (Bouillon et al., 2012). In Lake Kivu, seasonal variations of CH₄ in the main basin were driven by deepening of the mixolimnion and mixing of surface waters with deeper waters rich in CH₄ (Borges et al., 2011). In the Zambezi River (Zambia and Mozambique), interannual variability was relatively large for CO₂ and CH₄ and significantly higher concentrations were measured during wet seasons (Teodoru et al., 2015). However, interannual variability in N₂O was less pronounced and generally higher values were found during the dry season (Teodoru et al., 2015). In Kampala, Uganda, precipitation was a major driver for seasonal variation of CO₂, CH₄, and N₂O fluxes in subsurface flow wetland buffer strips due to its potential influence on hydraulic saturation affecting oxygen fluctuation (Bateganya et al., 2015).

Studies found the concentration and flux of GHGs are also strongly linked to environment and water quality (Table 3) but clear patterns have not yet been identified. In the Okavango Delta (Botswana), CH₄ emissions were highest during

the warmer, summer rainy season and lowest during cooler winter season, suggesting the emissions were probably regulated by water temperature (Gondwe and Masamba, 2014). However, Borges et al. (2015) found no significant correlation between water temperature and *p*CO₂ and dissolved CH₄ and N₂O in 11 SSA river systems, but there was a positive relationship between *p*CO₂ and dissolved organic C in six of the rivers. They also found the lowest N₂O values were observed at the highest *p*CO₂ and lowest % O₂ levels, suggesting the removal of N₂O by denitrification (Borges et al., 2015). In Lake Kivu (East Africa), the magnitude of CO₂ emissions to the atmosphere seems to depend mainly on inputs of dissolved inorganic carbon from deep geothermal springs rather than on the lake metabolism (Borges et al., 2014).

3.2.2 Greenhouse gas emissions from agricultural lands

Agricultural GHG emissions in SSA are substantial, amounting to 26 % of the continent's total GHG emissions (Valentini et al., 2014) compared to 8.4 % of total GHG emissions in the USA (US EPA, 2016). Identifying controls on the emission of GHG from SSA agricultural land is challenging because both natural variations associated with climate and soil type and management factors including nutrients (particularly fertilization) and crop type affect GHG emissions.

Croplands

The effects of the amount and type of N input on N₂O emissions in croplands have been studied in several locations (Table 4). In western Kenya, the rate of N fertilizer application (0 to 200 kg N ha⁻¹) on maize fields had no significant effect on N₂O emissions (620 to 710 g N₂O–N ha⁻¹ for 99 days; Hickman et al., 2014). However, another study from western Kenya found a relationship between N input and N₂O emissions that was best described by an exponential model with the largest impact on N₂O emissions occurring when N inputs increased from 100 to 150 kg N ha⁻¹ (Hickman et al., 2015). An incubation study in Madagascar demonstrated that application of mixed urea and diammonium phosphate resulted in lower N₂O emissions (28 vs. 55 ng N₂O–N g⁻¹ h⁻¹ for 28 days, respectively) than a mixed application of urea and NPK fertilizer (Rabenarivo et al., 2014).

Incorporation of crop residues (tilling in crop residues following harvest) to the soil has frequently been proposed to increase soil fertility (Malhi et al., 2011); however, incorporation of crop residues also affects CO₂ and N₂O emissions (Table 3). In Tanzania, incorporation of maize straw and leaf residue into soil increased annual CO₂ fluxes substantially (emissions rose from 2.5 to 4.0 and 2.4 to 3.4 Mg C ha⁻¹ yr⁻¹ for clay and sand soils, respectively; Sugihara et al., 2012), although a study in Madagascar showed that incorporation of rice-straw residue resulted in larger fluxes of CO₂ but reduced N₂O emissions due to N immobilization (Rabenarivo

et al., 2014). In contrast, incorporation of *Tithonia diversifolia* (tithonia) leaves led to greater N_2O emissions compared to urea application in maize fields in Kenya (Sommer et al., 2015; Kimetu et al., 2007). The higher N_2O emissions after incorporation of *Tithonia diversifolia* were attributed to high levels of nitrate and available carbon in the soil caused by the application that subsequently enhanced denitrification rates. In incubation studies with cultivated soil from Ghana, N_2O emissions were significantly higher from soils amended with low C:N ratio clover residues compared to high C:N ratio barley residues (Frimpong et al., 2012). Increasing the proportion of maize in a cowpea–maize residue significantly decreased N_2O emissions compared to cowpea residue incorporation alone (Frimpong et al., 2011), again likely due to the higher C:N ratio of the maize residue compared with the cowpea. Another incubation study with cultivated soil from Ghana showed that N_2O emissions increased after incorporation of residues of three tropical plant species (*Vigna unguiculata*, *Mucuna pruriens*, and *Leucaena leucocephala*) and emissions were positively correlated with the C:N ratio of the residue, and negatively correlated with residue polyphenol content, polyphenol:N ratio and (lignin + polyphenol):N ratio (Frimpong and Baggs, 2010). It is rare for N_2O emissions to be positively correlated with the C:N ratio, and the authors of the study suggest that it was either because soil C was limiting denitrification rates or that release of N from the residues was slow (Frimpong and Baggs, 2010). The results demonstrate that the quality of residues (e.g., C:N ratio, N, lignin, and soluble polyphenol contents) affects GHG emissions and further studies are needed to clearly identify the relationship between them (Snyder et al., 2009; Mafongoya et al., 1997).

Adding an additional N (mineral or organic) when crop residues are incorporated into the soil could stimulate mineralization of crop residues, increase N-use efficiency and produce higher yields (e.g., Garcia-Ruiz and Baggs, 2007; Table 4). It was found that application of mixed crop residue or manure and inorganic fertilizers resulted in different response of CO_2 and N_2O emissions. In maize (*Zea mays* L.) and winter wheat (*Triticum aestivum* L.) fields in Zimbabwe, application of inorganic fertilizer (ammonium nitrate, $\text{NH}_4\text{NO}_3\text{-N}$) with manure increased CO_2 emissions (26 to 73 %) compared to sole application of manure (Nyamadzawo et al., 2014a). However, the mixed application resulted in lower yield-scaled N_2O emissions ($1.6\text{--}4.6\text{ g N}_2\text{O kg}^{-1}$ yield), compared to sole application of inorganic fertilizer ($6\text{--}14\text{ g N}_2\text{O kg}^{-1}$ yield; Nyamadzawo et al., 2014a). Similarly, in a maize field in Zimbabwe, N_2O emissions were lower after the application of composted manure and inorganic fertilizer ($\text{NH}_4\text{NO}_3\text{-N}$) compared to sole application of inorganic fertilizer. The same treatments, however, led to the opposite results for CO_2 emissions (Mapanda et al., 2011). In Mali, pearl millet (*Pennisetum glaucum*) fields treated with both manure and inorganic fertilizer urea emitted significantly less N_2O than plots receiving only urea fertilizer (Dick

et al., 2008). The lower N_2O emissions in soils amended with manure were attributed to the initial slow release and immobilization of mineral N and the consequently diminished pool of N available to be lost as N_2O (Nyamadzawo et al., 2014a, b; Mapanda et al., 2011; Dick et al., 2008). In an incubation study with cultivated soils from Zimbabwe, Ghana, and Kenya, combining organic residue (maize, calliandra, and tithonia) and urea fertilizers decreased N_2O emissions in coarse-textured soils but increased N_2O emissions in fine-textured soils due to the higher level of available N (Gentile et al., 2008).

The effects of crop type and management on GHG emissions have also been studied by several groups (Table 4). In Uganda, there were no significant differences in soil CO_2 effluxes from different crops (lettuces, cabbages, beans; Korerber et al., 2009). However, in Zimbabwe, rape production resulted in greater N_2O emissions (0.64–0.93 % of applied N was lost as N_2O) than tomatoes (0.40–0.51 % of applied N was lost as N_2O ; Masaka et al., 2014). In Kenya and Tanzania, Rosenstock et al. (2016) studied fluxes in four crop types and found large variation of CO_2 and N_2O flux both within and between crop types depending on environmental conditions and management. In Madagascar, N_2O emissions were not significantly affected by management practices such as direct seeding mulch-based cropping and traditional hand ploughing after harvesting (Chapuis-Lardy et al., 2009). However, the authors admitted the lack of difference between treatments may be partially due to the short duration of the experiment and suggested more complete monitoring to validate the observation. In highland Tanzanian maize fields, GHG fluxes were similar from soils under conventional and various conservation agriculture practices (Kimaro et al., 2016). However, when fluxes were yield-scaled the global warming potential ($\text{Mg CO}_2\text{ eq. Mg grain}^{-1}$) was lower from fields with reduced tillage plus mulch and leguminous trees ($2.1\text{--}3.1\text{ Mg CO}_2\text{ eq. Mg grain}^{-1}$) and from fields with reduced tillage plus mulch and nitrogen fertilizer ($1.9\text{--}2.3\text{ Mg CO}_2\text{ eq. Mg grain}^{-1}$) compared to fields under conventional agriculture ($1.9\text{--}8.3\text{ Mg CO}_2\text{ eq. Mg grain}^{-1}$; Kimaro et al., 2015). The results suggest that the effect of crop type and management on GHG emissions is difficult to predict and more research is needed to elucidate the relationship between crops, crop management, and GHG emissions.

Croplands were found to be both a sink and a source of CH_4 . In Burkina Faso, CH_4 flux rates from croplands ranged from -0.67 to $0.70\text{ kg CH}_4\text{-C ha}^{-1}\text{ yr}^{-1}$ (Brümmer et al., 2009), while in the Republic of Congo, CH_4 uptake was observed in cassava and peanut fields and a recently ploughed field (Delmas et al., 1991). However, cropped and fertilized dambos in Zimbabwe were consistently sources of CH_4 (13.4 to $66.7\text{ kg CH}_4\text{ ha}^{-1}\text{ yr}^{-1}$; Nyamadzawo et al., 2014b).

Grazing grassland

We only found two studies reporting GHG emissions in pastoral grasslands, and there remains a serious gap in our understanding of GHG emissions in these systems. Thomas (2012) found that soil CO₂ efflux from a Botswana grazing land was significantly higher in sandy soils where the biological soil crust (BSC) was removed and on calcrete where the BSC was buried under sand. The results indicated the importance of BSCs for C cycling in drylands and intensive grazing, which destroys BSCs through trampling and burial, will adversely affect C sequestration and storage (Thomas, 2012). Rosenstock et al. (2016) measured GHG fluxes from two pastures in western Kenya and found that CO₂ emissions ranged from 13.4 to 15.9 Mg CO₂ ha⁻¹ yr⁻¹, similar to levels found in the Amazon (Davidson et al., 2000).

Rice paddies

Rice paddies are well-known sources of CH₄ (e.g., Linquist et al., 2012). Experiments measuring GHG emissions in rice paddies have been conducted in Kenya (Tyler et al., 1988) and Zimbabwe (Nyamadzawo et al., 2013). In Kenya, CH₄ fluxes did not show any seasonal trend and did not indicate appreciable variability among two different strains of rice (Tyler et al., 1988). In Zimbabwe, intermittently saturated dambo rice paddies were a source of GHG and annual emissions (150-day growing season and 126 kg of applied N ha⁻¹) were estimated as 2.7 Mg CO₂ ha⁻¹ yr⁻¹, 12.5 kg CH₄ ha⁻¹, and 0.12 kg N₂O ha⁻¹ (Nyamadzawo et al., 2013). The IPCC (2006) uses a CH₄ emission factor of 1.30 kg CH₄ ha⁻¹ day⁻¹ for rice cultivation. The CH₄ emissions in the dambo rice paddies referred to here are much lower than the IPCC estimate (195 kg CH₄ ha⁻¹ = 1.3 kg CH₄ ha⁻¹ day⁻¹ × 150 days). The corresponding IPCC (2006) N₂O EF is 0.3 % for rice cultivation, and thus the N₂O emissions in the dambo rice paddies are also much lower than the IPCC estimate (0.40 kg N₂O–N ha⁻¹ = 126 kg N ha⁻¹ × 0.003; 0.63 kg N₂O ha⁻¹). These results suggest the potential for large deviations from expected emissions based on existing information.

Vegetable gardens

Greenhouse gas emissions from soils in vegetable gardens in peri-urban areas of Burkina Faso (Lompo et al., 2012) and Niger (Predotova et al., 2010) ranged from 73.3 to 132.0 Mg CO₂ ha⁻¹ yr⁻¹ and 53.4 to 177.6 kg N₂O ha⁻¹ yr⁻¹ (Tables 1 and S1).

In Burkina Faso, annual CO₂ and N₂O emissions from vegetable garden soils were 68 to 85 and 3 to 4 % of total C and N input, respectively (Lompo et al., 2012). The N₂O EFs (3 to 4 %) were higher than the IPCC default value of 1.0 % for all cropping systems (IPCC, 2006) and the global

N₂O EF of vegetable fields (0.94 %; Rezaei Rashti et al., 2015). The high N₂O EFs may be attributed to the excessive amount of applied N (2700–2800 kg N ha⁻¹ yr⁻¹) to get high yields in vegetable gardens since surplus N will stimulate N₂O production and inhibit biochemical N₂O reduction (e.g., Shcherbak et al., 2014; Kim et al., 2013). In vegetable gardens of Niger, a simple plastic sheet roofing and addition of ground rock phosphate to stored ruminant manure decreased N₂O gaseous losses by 50 % in comparison to dung directly exposed to the sun (Predotova et al., 2010).

Agroforestry

Soil CO₂ and N₂O emissions from African agroforestry were 38.6 Mg CO₂ ha⁻¹ yr⁻¹ and 0.2 to 26.7 kg N₂O ha⁻¹ yr⁻¹, respectively (Tables 1 and S1).

Improving fallow with N-fixing trees is a common agroforestry practice in several areas of Africa since it provides additional N to the soil that can be utilized by the subsequent cash crop (e.g., Makumba et al., 2007; Chikowo et al., 2004; Dick et al., 2001). However, the practice is also thought to increase CO₂ and N₂O emissions compared to conventional croplands (Table 4). Nitrous oxide emissions increased after incorporation of fallow residues and emissions were higher after incorporation of improved-fallow legume residues than natural-fallow residues (Baggs et al., 2006; Millar and Baggs, 2004; Millar et al., 2004). It was found that N₂O emissions were positively correlated with residue N content (Baggs et al., 2006; Millar et al., 2004) and negatively correlated with polyphenol content and its protein binding capacity (Millar and Baggs, 2004), soluble C-to-N ratio (Millar and Baggs, 2005), and lignin content (Baggs et al., 2006). While high residue N content likely leads to more available soil N and consequently increased N₂O production (Baggs et al., 2006; Millar and Baggs, 2005; Millar et al., 2004), polyphenols and lignins are both resistant to decomposition and could result in N immobilization resulting in less labile soil N and less N₂O production (Baggs et al., 2006; Millar and Baggs, 2004). Therefore, there may be potential to reduce N₂O emissions from agroforestry, but it may require ecological nutrient management (i.e., reduced inorganic fertilizer N inputs, accounting for N input from the legume trees; adding a C source such as a cover crop together with an N source) and rotation planning.

As in natural systems, N₂O emissions from agroforestry are also affected by rainfall events. In an incubation experiment in Uganda, N₂O emissions following simulated rainfall were at least 4 times larger for soils from under N-fixing trees (*Calliandra calothyrsus*) compared to soils with non-N fixing trees (*Grevillea robusta*; Dick et al., 2001). Similarly, in Mali, N₂O emissions were around 6 times higher from improved fallow with N-fixing trees (*Gliricidia sepium* and *Acacia colei*) following a simulated rainfall event compared with the emissions from soil under traditional fallow and continuous cultivation (Hall et al., 2006). In agroforestry

home gardens in Sudan, CO₂ and N₂O fluxes were positively correlated with soil moisture (Goenster et al., 2015).

3.2.3 Greenhouse gas emissions from land-use change

Land-use change has been recognized as the largest source of GHG emission in Africa (Valentini et al., 2014). Conversion rates of African natural lands, including forest, grassland and wetland, to agricultural lands have increased in recent years (Gibbs et al., 2010; FAO, 2010). The dominant type of land-use change has been the conversion of forest to agriculture with average deforestation rates of 3.4 Mha yr⁻¹ (FAO-STAT, 2014; Fig. 1). This land-use conversion results in an estimated additional release of $0.32 \pm 0.05 \times 10^9$ Mg C yr⁻¹ (Valentini et al., 2014) or $157.9 \pm 23.9 \times 10^9$ Mg CO₂ eq. in 1765 to 2005 (Kim and Kirschbaum, 2015), higher than fossil fuel emissions for Africa (Valentini et al., 2014). Land-use change affects soil GHG emissions due to changes in vegetation, soil, hydrology, and nutrient management (e.g., Kim and Kirschbaum, 2015) and the effects of land-use change on soil GHG emissions have been observed in African woodlands and savannah. Clearing and converting woodlands to croplands increased soil emissions of CO₂, CH₄, and N₂O (Mapanda et al., 2012), and soil CO₂ emissions from the converted croplands were higher than *Eucalyptus* plantations established in former natural woodlands (Mapanda et al., 2010). Changes in soil CO₂ efflux after afforestation of a tropical savannah with *Eucalyptus* were mostly driven by the rapid decomposition of savannah residues and the increase in *Eucalyptus* rhizospheric respiration (Nouvellon et al., 2012).

3.3 Suggested future research

Despite an increasing number of published estimates of GHG emissions in the last decade, there remains a high degree of uncertainty about the contribution of AFOLU to emissions in SSA (Table 5). To address this and reduce the uncertainty surrounding the estimates, additional GHG emission measurements that fully capture seasonal and annual variations across natural ecosystems and agricultural lands throughout SSA are urgently required. Identifying controlling factors and their effects on GHG fluxes is a pre-requisite to enhancing our understanding of efflux mechanisms and a necessary step towards scaling up the field-scale data to landscape, national, and continental scales (Table 5). It is important to know how GHG fluxes can be affected by management practices and natural events such as logging (e.g., Yashiro et al., 2008), thinning (e.g., Yohannes et al., 2013), storms (e.g., Vargas, 2012), pest outbreaks (e.g., Reed et al., 2014), fires (e.g., Andersson et al., 2004), and woody shrub encroachment (e.g., Smith and Johnson, 2004) in natural terrestrial systems and changing discharge (e.g., Wang et al., 2013) and water table (e.g., Yang et al., 2013) in aquatic systems. It is also important in agricultural lands to know how GHG fluxes are affected by management factors such as soil compaction

(e.g., Ball et al., 1999), tillage (e.g., Sheehy et al., 2013), removal of crop residues (Jin et al., 2014), incorporation of crop residues and synthetic fertilizer (e.g., Nyamadzawo et al., 2014a), N input (whether organic or inorganic; e.g., Hickman et al., 2015), and crop type (e.g., Masaka et al., 2014). However, because management and soil physical–chemical interactions cause different responses in soil GHG emissions (e.g., Pelster et al., 2012), it is critical to measure these interaction effects in the African context. The effect of predicted climatic change in Africa such as increased temperature (e.g., Dijkstra et al., 2012), changing rainfall patterns (e.g., Hall et al., 2006), increase in droughts incidence (e.g., Berger et al., 2013), rewetting effects (e.g., Kim et al., 2012b), and increased atmospheric CO₂ concentration (e.g., Lane et al., 2013) also require further testing using laboratory and field experiments. Future research should consider the wider GHG budget of agriculture and include all the various (non-soil) components such as fuel use, as well as embodied emissions in chemical inputs.

Where possible, studies should seek to identify and separate the processes contributing to efflux of soil CO₂ (e.g., autotrophic and heterotrophic sources), CH₄ (e.g., methanogenesis and methanotrophy), and N₂O (e.g., nitrification, denitrification, and nitrifier denitrification) and link new knowledge of microbial communities (e.g., functional gene abundance) to GHG emissions rates. This is important because the consequences of increasing GHG emissions depend on the mechanism responsible. For example, if greater soil CO₂ efflux is primarily due to autotrophic respiration from plant roots, then it simply reflects greater plant growth. If, however, it is due to heterotrophic microbial respiration of soil organic carbon, then it represents a depletion of soil organic matter and a net transfer of C from soil to the atmosphere. Currently, there are very few studies that differentiate these sources, making it impossible to truly determine the consequences and implications on changes in soil GHG efflux.

Land-use change has been recognized as the largest source of GHG emission in Africa (Valentini et al., 2014). Hence, various types of conversion from natural lands to different land-use types should be assessed to know how these changes may affect the GHG budget (e.g., Kim and Kirschbaum, 2015). The focus of the assessment should be on deforestation and wetland drainage, followed by a conversion to agricultural lands, since they are dominant types of land-use change in Africa (Valentini et al., 2014).

Throughout the study, we identified various trade-offs including increased CO₂ emission following forest thinning management, increased GHG emissions in land-use changes, very high N₂O emissions in vegetable gardens due to excessive N input to get high yields, increased CO₂ and N₂O emission in incorporation of crop residues to the soil and agroforestry practices, and exponentially increased N₂O emission and yield-scaled N₂O emissions in excessive N input. More work is needed, however, before we have a clear picture of the net impact of the tradeoffs and drivers.

Table 5. Summary of status of knowledge of greenhouse gas emission processes, control factors, estimation, and model prediction.

	CO ₂			N ₂ O			CH ₄		
	Processes & control factors	Annual flux estimate	Model prediction	Processes & control factors	Annual flux estimate	Model prediction	Processes & control factors	Annual flux estimate	Model prediction
Forest/plantation/woodland	1	2	4	3	3	4	3	3	4
Savannah	2	3	4	3	4	4	3	4	4
Aquatic systems	2	3	4	3	3	4	2	3	4
Cropland	2	3	4	2	2	4	3	4	4
Agroforestry	3	4	4	2	3	4	4	4	4
Vegetable gardens	3	4	4	3	4	4	4	4	4
Rice field	3	4	4	3	4	4	4	4	4
Grazing grassland	3	4	4	4	4	4	4	4	4

1: Robust knowledge – incremental work needed. 2: Existing knowledge base – coordinated work needed. 3: A growing knowledge base – with many gaps and comprehensive work still needed. 4: Emerging knowledge base – significant research effort required.

3.4 Strategic approaches for data acquisition

A strategic plan for acquisition of soil GHG emission data in sub-Saharan Africa is required. The success of any plan is dependent on long-term investment, stakeholder involvement, technical skill, and supporting industries, which have not always been available in the region (Olander et al., 2013; Franks and Hadingham, 2012). A major challenge is to address the lack of consistency in the various methodologies used to quantify GHG emissions (Rosenstock et al., 2013). Relatively low cost and simple techniques can be used to determine GHG emission estimates in the first instance. Soil CO₂ fluxes can be quantified with a soda lime method (Tufekcioglu et al., 2001; Cropper et al., 1985; Edwards, 1982) or an infrared gas analyzer (Bastviken et al., 2015; Verhot et al., 2008; Lee and Jose, 2003), and these do not require advanced technology or high levels of resource to undertake. Later, other GHG such as N₂O and CH₄ fluxes in addition to CO₂ flux can be measured with more advanced technology (e.g., gas chromatography, photoacoustic spectroscopy, or laser gas analyzers). Initially, the measurement can be conducted using manual gas chambers with periodical sampling frequencies. The sampling interval can be designed so that it is appropriate to the particular type of land use or ecosystem, management practices, and/or for capturing the effects of episodic events (e.g., Parkin, 2008). For example, GHG measurement should be more during potentially high GHG emission periods following tillage and fertilizer applications and rewetting by natural rainfalls or irrigation. With more advanced technology and utilization of automatic chamber systems, measurements can be conducted at a much higher frequency with relative ease.

In order for the challenges associated with improving our understanding of GHG emissions from African soils, it is critical to establish networks of scientists and scientific bodies both within Africa and across the world. Good communication and collaboration between field researchers and the modeling community should also be established during the initial stages of research, so results obtained from field scientists can be effectively used for model development and to

generate hypotheses to be tested in the field and laboratory (de Bruijn et al., 2009).

Furthermore, lessons learned from scientific experiments can only really be successfully implemented by farmers if local stakeholders are involved from the start and throughout (see, for example, Stringer et al., 2012). Interviews, focus-groups, on-site or farm demonstrations, local capacity building training, local farmers, and extension staff can all improve dialogue and understanding between local communities and scientists, ultimately improving the likelihood of successful GHG emission and mitigation strategies. These will equip local researchers and stakeholders (including farmers and extension staff) with state-of-the-art methodologies and help motivate them to develop their GHG mitigation measures and assist them in understanding their roles and contributions to global environmental issues. Moreover, data acquisition will be determined not only by technical but also by sociopolitical (and economic) barriers in sub-Saharan Africa. These problems not only affect data acquisition but are also the driving forces for GHG emissions due to land-use change events.

4 Conclusions

This paper synthesizes the available data on GHG emissions from African agricultural and natural lands. Emissions of CO₂, CH₄, and N₂O in a variety of environments (forests, savannahs, termite mounds, salt pans, agricultural areas, and water bodies) were considered. Two broad conclusions can be drawn from the work. The first one is that African natural and agricultural lands may be a significant source of GHG and that the emissions may increase through land-use change and management strategies. Secondly, there are huge research gaps. Africa is a vast continent, with a multitude of land uses, climates, soils, and ecosystems. Field-based data on soil GHG emissions from many areas, soil types, and environments are extremely sparse, and as a result our understanding of Africa's contribution to global GHG emissions remains incomplete and highly uncertain. There is an urgent need to develop and agree on a strategy for addressing this

data gap. The strategy needs to involve identifying priorities for data acquisition, utilizing appropriate technologies, and establishing networks and collaboration.

5 Data availability

We have created a blog entitled “Greenhouse gas emissions in Africa: study summary and database” (<http://ghginafrica.blogspot.com/>) and an open-access database, which can be modified by the users, entitled “Soil greenhouse gas emissions in Africa database” (linked in the blog) based on this review. In the blog, we have posted a technical summary of each section of this review, where comments can be left under the posts. The database contains detailed information on the studies reported on GHG emissions, such as ecosystem and land-use types, location, climate, vegetation type, crop type, fertilizer type, N input rate, soil properties, GHGs emission measurement periods, N₂O EF, and corresponding reference. The database is hosted in web-based spreadsheets and is easily accessible and modified. The authors do not have any relationship with the companies currently being used to host the blog or databases.

The Supplement related to this article is available online at doi:10.5194/bg-13-4789-2016-supplement.

Acknowledgements. We are grateful for the numerous researchers and technicians who provided invaluable data. It is impossible to cite all the references due to limited space allowed and we apologize for the authors whose work has not been cited. We are also grateful to Benjamin Bond-Lamberty and Rodrigo Vargas for insightful comments, Luis Lassaletta for guiding us with N application rates in Africa, and Antony Smith for creating maps showing study sites. Alberto Sanz-Cobena gratefully acknowledges the Spanish Ministry of Science and Innovation and the Autonomous Community of Madrid for their economic support through the NEREA project (AGL2012-37815-C05-01, AGL2012-37815-C05-04), the Agrisost Project (S2013/ABI-2717), and the FACCE JPI MACSUR project. Dong-Gill Kim acknowledges support from Research and Development Office, Wondo Genet College, and the IAEA Coordinated Research Project (CRP D1 50.16). David Pelster and Todd S. Rosenstock would like to thank the CGIAR Research Program on Climate Change, Agriculture, and Food Security and its Standard Assessment of Mitigation Potential and Livelihoods in Smallholder Systems (SAMPLES) Programme for technical and financial support.

Edited by: M. Weintraub

Reviewed by: three anonymous referees

References

- Andersson, M., Michelsen, A., Jensen, M., and Kjoller, A.: Tropical savannah woodland: Effects of experimental fire on soil microorganisms and soil emissions of carbon dioxide, *Soil Biol. Biochem.*, 36, 849–858, 2004.
- Baggs, E., Chebii, J., and Ndufa, J.: A short-term investigation of trace gas emissions following tillage and no-tillage of agroforestry residues in western Kenya, *Soil Till. Res.*, 90, 69–76, 2006.
- Ball, B. C., Scott, A., and Parker, J. P.: Field N₂O, CO₂ and CH₄ fluxes in relation to tillage, compaction and soil quality in Scotland, *Soil Till. Res.*, 53, 29–39, 1999.
- Barton, L., Wolf, B., Rowlings, D., Scheer, C., Kiese, R., Grace, P., Stefanova, K., and Butterbach-Bahl, K.: Sampling frequency affects estimates of annual nitrous oxide fluxes, *Sci. Rep.*, 5, 15912, doi:10.1038/srep15912, 2015.
- Bastviken, D., Sundgren, I., Natchimuthu, S., Reyier, H., and Gålfalk, M.: Technical Note: Cost-efficient approaches to measure carbon dioxide (CO₂) fluxes and concentrations in terrestrial and aquatic environments using mini loggers, *Biogeosciences*, 12, 3849–3859, doi:10.5194/bg-12-3849-2015, 2015.
- Bateganya, N. L., Mentler, A., Langergraber, G., Busulwa, H., and Hein, T.: Carbon and nitrogen gaseous fluxes from subsurface flow wetland buffer strips at mesocosm scale in east Africa, *Ecol. Eng.*, 85, 173–184, 2015.
- Berger, S., Jung, E., Köpp, J., Kang, H., and Gebauer, G.: Monsoon rains, drought periods and soil texture as drivers of soil N₂O fluxes – Soil drought turns East Asian temperate deciduous forest soils into temporary and unexpectedly persistent N₂O sinks, *Soil Biol. Biochem.*, 57, 273–281, 2013.
- Birch, H. F.: Mineralisation of plant nitrogen following alternate wet and dry conditions, *Plant Soil*, 20, 43–49, 1964.
- Bombelli, A., Henry, M., Castaldi, S., Adu-Bredu, S., Arneth, A., de Grandcourt, A., Grieco, E., Kutsch, W. L., Lehsten, V., Rasile, A., Reichstein, M., Tansey, K., Weber, U., and Valentini, R.: An outlook on the Sub-Saharan Africa carbon balance, *Biogeosciences*, 6, 2193–2205, doi:10.5194/bg-6-2193-2009, 2009.
- Bond-Lamberty, B. and Thomson, A. M.: Temperature-associated increases in the global soil respiration record, *Nature*, 464, 579–582, 2010.
- Borges, A. V., Abril, G., Delille, B., Descy, J.P., and Darchambeau, F.: Diffusive methane emissions to the atmosphere from Lake Kivu (Eastern Africa), *J. Geophys. Res.*, 116, G03032, doi:10.1029/2011JG001673, 2011.
- Borges, A. V., Morana, C., Bouillon, S., Servais, P., Descy, J.-P., and Darchambeau, F.: Carbon cycling of Lake Kivu (East Africa): net autotrophy in the epilimnion and emission of CO₂ to the atmosphere sustained by geogenic inputs, *PLoS one*, 9, e109500, doi:10.1371/journal.pone.0109500, 2014.
- Borges, A. V., Darchambeau, F., Teodoru, C. R., Marwick, T. R., Tammo, F., Geeraert, N., Omengo, F. O., Guerin, F., Lambert, T., Morana, C., Okuku, E., and Bouillon, S.: Globally significant greenhouse-gas emissions from African inland waters, *Nat. Geosci.*, 8, 637–642, doi:10.1038/ngeo2486, 2015.
- Bouillon, S., Yambélé, A., Spencer, R. G. M., Gillikin, D. P., Hernes, P. J., Six, J., Merckx, R., and Borges, A. V.: Organic matter sources, fluxes and greenhouse gas exchange in the Oubangui River (Congo River basin), *Biogeosciences*, 9, 2045–2062, doi:10.5194/bg-9-2045-2012, 2012.

- Bouwman, A. F., Beusen, A. H. W., and Billen, G.: Human alteration of the global nitrogen and phosphorus soil balances for the period 1970–2050, *Global Biogeochem. Cy.*, 23, GB0A04, doi:10.1029/2009GB003576, 2009.
- Bouwman, L., Goldewijk, K. K., Van Der Hoek, K. W., Beusen, A. H. W., Van Vuuren, D. P., Willems, J., Rufino, M. C., and Stehfest, E.: Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period, *P. Natl. Acad. Sci. USA*, 110, 20882–20887, doi:10.1073/pnas.1012878108, 2013.
- Brümmer, C., Papen, H., Wassmann, R., and Brüggemann, N.: Fluxes of CH₄ and CO₂ from soil and termite mounds in south Sudanian savanna of Burkina Faso (West Africa), *Global Biogeochem. Cy.*, 23, GB1001, doi:10.1029/2008GB003237, 2009.
- Brunet, F., Dubois, K., Veizer, J., Nkoue Ndong, G. R., Ndam Ngoupayou, J. R., Boeglin, J. L., and Probst, J. L.: Terrestrial and fluvial carbon fluxes in a tropical watershed: Nyong basin, Cameroun, *Chem. Geol.*, 2, 563–572, 2009.
- Caquet, B., De Grandcourt, A., Thongo M'bou, A., Epron, D., Kinana, A., Saint André, L., and Nouvellon, Y.: Soil carbon balance in a tropical grassland: Estimation of soil respiration and its partitioning using a semi-empirical model, *Agr. Forest. Meteorol.*, 158–159, 71–79, 2012.
- Castaldi, S., de Grandcourt, A., Rasile, A., Skiba, U., and Valentini, R.: CO₂, CH₄ and N₂O fluxes from soil of a burned grassland in Central Africa, *Biogeosciences*, 7, 3459–3471, doi:10.5194/bg-7-3459-2010, 2010.
- Chapuis-Lardy, L., Metay, A., Martinet, M., Rabenarivo, M., Toucet, J., Douzet, J. M., Razafimbelo, T., Rabeharisoa, L., and Rakotoarisoa, J.: Nitrous oxide fluxes from malagasy agricultural soils, *Geoderma*, 148, 421–427, 2009.
- Chikowo, R., Mapfumo, P., Nyamugafata, P., and Giller, K. E.: Mineral N dynamics, leaching and nitrous oxide losses under maize following two-year improved fallows on a sandy loam soil in Zimbabwe, *Plant Soil*, 259, 315–330, 2004.
- Ciais, P., Bombelli, A., Williams, M., Piao, S. L., Chave, J., Ryan, C. M., Henry, M., Brender, P., and Valentini, R.: The Carbon Balance of Africa: Synthesis of Recent Research Studies, *Philos. T. R. Soc. A*, 269, 2038–2057, 2011.
- Cropper Jr., W., Ewel, K. C., and Raich, J.: The measurement of soil CO₂ evolution in situ, *Pedobiologia*, 28, 35–40, 1985.
- Davidson, E. A., Verchot, L. V., Cattaneo, J. H., Ackerman, I. L., and Carvalho, J.: Effects of soil water content on soil respiration in forests and cattle pastures of eastern Amazonia, *Biogeochemistry*, 48, 53–69, 2000.
- de Bruijn, A. M. G., Butterbach-Bahl, K., Blagodatsky, S., and Grote, R.: Model evaluation of different mechanisms driving freeze-thaw N₂O emissions, *Agric. Ecosyst. Environ.*, 133, 196–207, 2009.
- Delmas, R. A., Marengo, A., Tathy, J. P., Cros, B., and Baudet, J. G. R.: Sources and sinks of methane in African savanna. CH₄ emissions from biomass burning, *J. Geophys. Res.*, 96, 7287–7299, 1991.
- DelSontro, T., Kunz, M. J., Kempter, T., Wüest, A., Wehrli, B., and Senn, D. B.: Spatial heterogeneity of methane ebullition in a large tropical reservoir, *Environ. Sci. Technol.*, 45, 9866–9873, doi:10.1021/es2005545, 2011.
- Díaz-Pinés, E., Schindlbacher, A., Godino, M., Kitzler, B., Jandl, R., Zechmeister-Boltenstern, S., and Rubio, A.: Effects of tree species composition on the CO₂ and N₂O efflux of a Mediterranean mountain forest soil, *Plant Soil*, 384, 243–257, 2014.
- Dick, J., Skiba, U., and Wilson J.: The effect of rainfall on NO and N₂O emissions from Ugandan agroforest soils, *Phyton*, 41, 73–80, 2001.
- Dick, J., Skiba, U., Munro, R., and Deans, D.: Effect of N-fixing and non n-fixing trees and crops on NO and N₂O emissions from Senegalese soils, *J. Biogeogr.*, 33, 416–423, 2006.
- Dick, J., Kaya, B., Soutoura, M., Skiba, U., Smith, R., Niang, A., and Tabo, R.: The contribution of agricultural practices to nitrous oxide emissions in semi-arid Mali, *Soil Use Manage.*, 24, 292–301, 2008.
- Dijkstra, F. A., Prior, S. A., Runion, G. B., Torbert, H. A., Tian, H., Lu, C., and Venterea, R. T.: Effects of elevated carbon dioxide and increased temperature on methane and nitrous oxide fluxes: evidence from field experiments, *Front. Ecol. Environ.*, 10, 520–527, 2012.
- Dutaur, L. and Verchot, L. V.: A global inventory of the soil CH₄ sink, *Global Biogeochem. Cy.*, 21, GB4013, doi:10.1029/2006gb002734, 2007.
- Edwards, N.: The use of soda-lime for measuring respiration rates in terrestrial systems, *Pedobiologia*, 23, 321–330, 1982.
- Epron, D., Nouvellon, Y., Roupsard, O., Mouvondy, W., Mabiala, A., Saint-André, L., Joffre, R., Jourdan, C., Bonnefond, J.-M., Berbigier, P., and Hamel, O.: Spatial and temporal variations of soil respiration in a eucalyptus plantation in Congo, *Forest Ecol. Manage.*, 202, 149–160, 2004.
- Epron, D., Nouvellon, Y., Mareschal, L., e Moreira, R. M., Koutika, L.-S., Geneste, B., Delgado-Rojas, J. S., Laclau, J.-P., Sola, G., and de Moraes Gonçalves, J. L.: Partitioning of net primary production in eucalyptus and acacia stands and in mixed-species plantations: Two case-studies in contrasting tropical environments, *Forest Ecol. Manage.*, 301, 102–111, 2013.
- Fan, Z., Neff, J. C., and Hanan, N. P.: Modeling pulsed soil respiration in an African savanna ecosystem, *Agr. Forest. Meteorol.*, 200, 282–292, 2015.
- FAO: Global Forest Resources Assessment 2010, FAO Forestry Paper 163, Food and Agriculture Organization of the United Nations, Rome, 340 pp., available at: <http://www.fao.org/forestry/fra/fra2010/en/> (last access: 1 October 2015), 2010.
- FAOSTAT: Food and agriculture organization of the United Nations, <http://faostat.fao.org/site/377/default.aspx#ancor>, last access: 1 October 2015.
- Franks, J. R. and Hadingham, B.: Reducing greenhouse gas emissions from agriculture: Avoiding trivial solutions to a global problem, *Land Use Policy*, 29, 727–736, 2012.
- Frimpong, K. A. and Baggs, E. M.: Do combined applications of crop residues and inorganic fertilizer lower emission of N₂O from soil?, *Soil Use Manage.*, 26, 412–424, 2010.
- Frimpong, K. A., Yawson, D. O., Baggs, E. M., and Agyarko, K.: Does incorporation of cowpea-maize residue mixes influence nitrous oxide emission and mineral nitrogen release in a tropical luvisol?, *Nutr. Cycl. Agroecosys.*, 91, 281–292, 2011.
- Frimpong, K. A., Yawson, D. O., Agyarko, K., and Baggs, E. M.: N₂O emission and mineral N release in a tropical Acrisol incorporated with mixed cowpea and maize residues, *Agron.*, 2, 167–186, 2012.

- Garcia-Ruiz, R. and Baggs, E.: N₂O emission from soil following combined application of fertiliser-N and ground weed residues, *Plant Soil*, 299, 263–274, 2007.
- Gentile, R., Vanlauwe, B., Chivenge, P., and Six, J.: Interactive effects from combining fertilizer and organic residue inputs on nitrogen transformations, *Soil Biol. Biochem.*, 40, 2375–2384, 2008.
- Gharahi Ghehi, N., Werner, C., Cizungu Ntaboba, L., Mbonigaba Muhinda, J. J., Van Ranst, E., Butterbach-Bahl, K., Kiese, R., and Boeckx, P.: Spatial variations of nitrogen trace gas emissions from tropical mountain forests in Nyungwe, Rwanda, *Biogeosciences*, 9, 1451–1463, doi:10.5194/bg-9-1451-2012, 2012.
- Gharahi Ghehi, N., Werner, C., Hufkens, K., Kiese, R., Van Ranst, E., Nsabimana, D., Wallin, G., Klemmedtsson, L., Butterbach-Bahl, K., and Boeckx, P.: N₂O and NO emission from the Nyungwe tropical highland rainforest in Rwanda, *Geoderma Regional*, 2–3, 41–49, 2014.
- Gibbs, H. K., Ruesch, A. S., Achard, F., Clayton, M. K., Holmgren, P., Ramankutty, N., and Foley, J. A.: Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s, *P. Natl. Acad. Sci. USA*, 107, 16732–16737, 2010.
- Goenster, S., Wiehle, M., Predotova, M., Gebauer, J., Ali, A. M., and Buerkert, A.: Gaseous emissions and soil fertility of homegardens in the Nuba Mountains, Sudan, *J. Plant Nutr. Soil Sci.*, 178, 413–424, 2015.
- Gondwe, M. J. and Masamba, W. R.: Spatial and temporal dynamics of diffusive methane emissions in the Okavango delta, northern Botswana, Africa, *Wetlands Ecol. Manage.*, 22, 63–78, 2014.
- Hall, N. M., Kaya, B., Dick, J., Skiba, U., Niang, A., and Tabo, R.: Effect of improved fallow on crop productivity, soil fertility and climate-forcing gas emissions in semi-arid conditions, *Biol. Fert. Soils*, 42, 224–230, 2006.
- Hanson, R. S. and Hanson, T. E.: Methanotrophic bacteria, *Microbiol. Molecular Biol. Rev.*, 60, 439–471, 1996.
- Hickman, J. E., Havlikova, M., Kroeze, C., and Palm, C. A.: Current and future nitrous oxide emissions from African agriculture, *Curr. Opin. Environ. Sustain.*, 3, 370–378, 2011.
- Hickman, J. E., Palm, C., Mutuo, P., Melillo, J., and Tang, J.: Nitrous oxide (N₂O) emissions in response to increasing fertilizer addition in maize (*Zea mays* L.) agriculture in western Kenya, *Nutr. Cycl. Agroecosys.*, 100, 177–187, 2014.
- Hickman, J. E., Tully, K. L., Groffman, P. M., Diru, W., and Palm, C. A. C. J. G.: A potential tipping point in tropical agriculture: Avoiding rapid increases in nitrous oxide fluxes from agricultural intensification in Kenya, *J. Geophys. Res.*, 12, 938–951, doi:10.1002/2015JG002913, 2015.
- IPCC: Intergovernmental Panel on Climate Change: Guidelines for national greenhouse gas inventories, available at: <http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html>, (last access: 27 March 2015), Geneva, Switzerland, 2006.
- IPCC: Summary for policymakers, in: *Climate Change 2014, Mitigation of Climate Change*, contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., Kriemann, B., Savolainen, J., Schlömer, S., von Stechow, C., Zwickel, T., and Minx, J. C., Cambridge University Press, Cambridge, UK and New York, NY, USA, 1–30, 2014.
- Iqbal, J., Castellano, M. J., and Parkin, T. B.: Evaluation of photoacoustic infrared spectroscopy for simultaneous measurement of N₂O and CO₂ gas concentrations and fluxes at the soil surface, *Glob. Change Biol.*, 19, 327–336, 2013.
- Jin, V. L., Baker, J. M., Johnson, J. M. F., Karlen, D. L., Lehman, R. M., Osborne, S. L., Sauer, T. J., Stott, D. E., Varvel, G. E., and Venterea, R. T.: Soil greenhouse gas emissions in response to corn stover removal and tillage management across the us corn belt, *BioEnergy Res.*, 7, 517–527, 2014.
- Kim, D.-G.: Estimation of net gain of soil carbon in a nitrogen-fixing tree and crop intercropping system in sub-Saharan Africa: Results from re-examining a study, *Agroforest. Sys.*, 86, 175–184, 2012.
- Kim, D.-G. and Kirschbaum, M. U.: The effect of land-use change on the net exchange rates of greenhouse gases: A compilation of estimates, *Agr. Ecosyst. Environ.*, 208, 114–126, 2015.
- Kim, D.-G., Mu, S., Kang, S., and Lee, D.: Factors controlling soil CO₂ effluxes and the effects of rewetting on effluxes in adjacent deciduous, coniferous, and mixed forests in Korea, *Soil Biol. Biochem.*, 42, 576–585, 2010.
- Kim, D.-G., Vargas, R., Bond-Lamberty, B., and Turetsky, M. R.: Effects of soil rewetting and thawing on soil gas fluxes: a review of current literature and suggestions for future research, *Biogeosciences*, 9, 2459–2483, doi:10.5194/bg-9-2459-2012, 2012.
- Kim, D.-G., Hernandez-Ramirez, G., and Giltrap, D.: Linear and nonlinear dependency of direct nitrous oxide emissions on fertilizer nitrogen input: A meta-analysis, *Agr. Ecosyst. Environ.*, 168, 53–65, 2013.
- Kim, Y. S., Makoto, K., Takakai, F., Shibata, H., Satomura, T., Takagi, K., Hatano, R., and Koike, T.: Greenhouse gas emissions after a prescribed fire in white birch-dwarf bamboo stands in northern Japan, focusing on the role of charcoal, *Eur. J. Forest Res.*, 130, 1031–1044, 2011.
- Kimaro, A., Mpanda, M., Rioux, J., Aynekulu, E., Shaba, S., Thiong'o, M., Mutuo, P., Abwanda, S., Shepherd, K., Neufeldt, H., and Rosenstock, T.: Is conservation agriculture “climate-smart” for maize farmers in the highlands of Tanzania?, *Nutr. Cycl. Agroecosys.*, 105, 217–228, doi:10.1007/s10705-015-9711-8, 2016.
- Kimetu, J., Mugendi, D., Bationo, A., Palm, C., Mutuo, P., Kihara, J., Nandwa, S., and Giller, K.: Partial balance of nitrogen in a maize cropping system in humid nitisol of Central Kenya, *Nutr. Cycl. Agroecosys.*, 76, 261–270, 2007.
- Knowles, R.: Denitrification, *Microbiol. Rev.*, 46, 43–70, 1982.
- Koerber, G. R., Edwards-Jones, G., Hill, P. W., Nyeko, P., York, E. H., and Jones, D. L.: Geographical variation in carbon dioxide fluxes from soils in agro-ecosystems and its implications for life-cycle assessment, *J. Appl. Ecol.*, 46, 306–314, 2009.
- Koné, Y. J. M., Abril, G., Kouadio, K. N., Delille, B., and Borges, A. V.: Seasonal variability of carbon dioxide in the rivers and lagoons of Ivory Coast (West Africa), *Estuar. Coast.*, 32, 246–260, 2009.
- Kowalchuk, G. A. and Stephen, J. R.: Ammonia-oxidizing bacteria: A model for molecular microbial ecology, *Annu. Rev. Microbiol.*, 55, 485–529, 2001.
- Kulmala, L., Aaltonen, H., Berninger, F., Kieloaho, A.-J., Levula, J., Bäck, J., Hari, P., Kolari, P., Korhonen, J. F. J., Kulmala, M., Nikinmaa, E., Pihlatie, M., Vesala, T., and Pumpanen, J.: Changes in biogeochemistry and carbon fluxes in a boreal forest

- after the clear-cutting and partial burning of slash, *Agr. Forest. Meteorol.*, 188, 33–44, 2014.
- Lamade, E., Djegui, N., and Leterme, P.: Estimation of carbon allocation to the roots from soil respiration measurements of oil palm, *Plant Soil*, 181, 329–339, 1996.
- Lane, R. W., Menon, M., McQuaid, J. B., Adams, D. G., Thomas, A. D., Hoon, S. R., and Dougill, A. J.: Laboratory analysis of the effects of elevated atmospheric carbon dioxide on respiration in biological soil crusts, *J. Arid Environ.*, 98, 52–59, 2013.
- Lee, K.-H. and Jose, S.: Soil respiration and microbial biomass in a pecan-cotton alley cropping system in southern USA, *Agroforest. Syst.*, 58, 45–54, 2003.
- Linquist, B. A., Adviento-Borbe, M. A., Pittelkow, C. M., van Kessel, C., and van Groenigen, K. J.: Fertilizer management practices and greenhouse gas emissions from rice systems: A quantitative review and analysis, *Field Crops Res.*, 135, 10–21, 2012.
- Lompo, D. J.-P., Sangaré, S. A. K., Compaoré, E., Papoada Sedogo, M., Predotova, M., Schlecht, E., and Buerkert, A.: Gaseous emissions of nitrogen and carbon from urban vegetable gardens in bobo-dioulasso, Burkina Faso, *J. Plant Nutr. Soil Sci.*, 175, 846–853, 2012.
- Macdonald, J. A., Eggleton, P., Bignell, D. E., Forzi, F., and Fowler, D.: Methane emission by termites and oxidation by soils, across a forest disturbance gradient in the mbalmayo forest reserve, Cameroon, *Glob. Change Biol.*, 4, 409–418, 1998.
- Mafongoya, P., Giller, K., and Palm, C.: Decomposition and nitrogen release patterns of tree prunings and litter, *Agroforest. Syst.*, 38, 77–97, 1997.
- Makumba, W., Akinnifesi, F. K., Janssen, B., and Oenema, O.: Long-term impact of a gliricidia-maize intercropping system on carbon sequestration in southern Malawi, *Agr. Ecosyst. Environ.*, 118, 237–243, 2007.
- Malhi, S., Nyborg, M., Solberg, E., Dyck, M., and Puurveen, D.: Improving crop yield and N uptake with long-term straw retention in two contrasting soil types, *Field Crops Res.*, 124, 378–391, 2011.
- Mann, P. J., Spencer, R. G., Dinga, B., Poulsen, J. R., Hernes, P., Fiske, G., Salter, M. E., Wang, Z. A., Hoering, K. A., and Six, J.: The biogeochemistry of carbon across a gradient of streams and rivers within the Congo basin, *J. Geophys. Res.-Biogeo.*, 119, 687–702, 2014.
- Mapanda, F., Mupini, J., Wuta, M., Nyamangara, J., and Rees, R.: A cross-ecosystem assessment of the effects of land cover and land use on soil emission of selected greenhouse gases and related soil properties in Zimbabwe, *Eur. J. Soil Sci.*, 61, 721–733, 2010.
- Mapanda, F., Wuta, M., Nyamangara, J., and Rees, R. M.: Effects of organic and mineral fertilizer nitrogen on greenhouse gas emissions and plant-captured carbon under maize cropping in Zimbabwe, *Plant Soil*, 343, 67–81, 2011.
- Mapanda, P., Wuta, M., Nyamangara, J., Rees, R., and Kitzler, B.: Greenhouse gas emissions from savanna (miombo) woodlands: Responses to clearing and cropping, *Afr. Crop Sci. J.*, 20, 385–400, 2012.
- Masaka, J., Nyamangara, J., and Wuta, M.: Nitrous oxide emissions from wetland soil amended with inorganic and organic fertilizers, *Arch. Agron. Soil Sci.*, 60, 1363–1387, 2014.
- Merbold, L., Ziegler, W., Mukelabai, M. M., and Kutsch, W. L.: Spatial and temporal variation of CO₂ efflux along a disturbance gradient in a *miombo* woodland in Western Zambia, *Biogeochemistry*, 8, 147–164, doi:10.5194/bg-8-147-2011, 2011.
- Millar, N. and Baggs, E. M.: Chemical composition, or quality, of agroforestry residues influences N₂O emissions after their addition to soil, *Soil Biol. Biochem.*, 36, 935–943, 2004.
- Millar, N. and Baggs, E. M.: Relationships between N₂O emissions and water-soluble c and n contents of agroforestry residues after their addition to soil, *Soil Biol. Biochem.*, 37, 605–608, 2005.
- Millar, N., Ndufa, J., Cadisch, G., and Baggs, E.: Nitrous oxide emissions following incorporation of improved-fallow residues in the humid tropics, *Global Biogeochem. Cy.*, 18, GB1032, doi:doi:10.1029/2003GB002114, 2004.
- Motulsky, H. J. and Christopoulos, A.: Fitting models to biological data using linear and nonlinear regression: a practical guide to curve fitting, Oxford University Press, New York, 2004.
- Nouvellon, Y., Epron, D., Marsden, C., Kinana, A., Le Maire, G., Deleporte, P., Saint-André L., Bouillet, J.-P., and Laclau, J.-P.: Age-related changes in litter inputs explain annual trends in soil CO₂ effluxes over a full eucalyptus rotation after afforestation of a tropical savannah, *Biogeochemistry*, 111, 515–533, 2012.
- Nyamadzawo, G., Gotosa, J., Muvengwi, J., Wuta, M., Nyamangara, J., Nyamugafata, P., and Smith, J. L.: The effect of catena position on greenhouse gas emissions from dambo located termite (*odontotermes transvaalensis*) mounds from central Zimbabwe, *Atmos. Climate Sci.*, 2, 501–509, doi:10.4236/acs.2012.24044, 2012.
- Nyamadzawo, G., Wuta, M., Chirinda, N., Mujuru, L., and Smith, J. L.: Greenhouse gas emissions from intermittently flooded (dambo) rice under different tillage practices in chiota smallholder farming area of Zimbabwe, *Atmos. Climate Sci.*, 3, 13–20, 2013.
- Nyamadzawo, G., Wuta, M., Nyamangara, J., Smith, J. L., and Rees, R. M.: Nitrous oxide and methane emissions from cultivated seasonal wetland (dambo) soils with inorganic, organic and integrated nutrient management, *Nutr. Cycl. Agroecosys.*, 100, 161–175, 2014a.
- Nyamadzawo, G., Shi, Y., Chirinda, N., Olesen, J. R., Mapanda, F., Wuta, M., Wu, W., Meng, F., Oelofse, M., de Neergaard, A., and Smith, J.: Combining organic and inorganic nitrogen fertilisation reduces N₂O emissions from cereal crops: a comparative analysis of China and Zimbabwe, *Mitig. Adapt. Strategies Glob. Chang.*, 1–13, doi:10.1007/s11027-014-9560-9, 2014b.
- Olander, L., Wollenberg, E., Tubiello, F., and Herold, M.: Advancing agricultural greenhouse gas quantification, *Environ. Res. Lett.*, 8, 011002, doi:10.1088/1748-9326/8/1/011002, 2013.
- Palm, C. A., Smukler, S. M., Sullivan, C. C., Mutuo, P. K., Nyadzi, G. I., and Walsh, M. G.: Identifying potential synergies and trade-offs for meeting food security and climate change objectives in sub-Saharan Africa, *P. Natl. Acad. Sci. USA*, 107, 19661–19666, 2010.
- Parkin, T. B.: Effect of sampling frequency on estimates of cumulative nitrous oxide emissions, *J. Environ. Qual.*, 37, 1390–1395, 2008.
- Pelster, D. E., Chantigny, M. H., Rochette, P., Angers, D. A., Rieueux, C., and Vanasse, A.: Nitrous oxide emissions respond differently to mineral and organic N sources in contrasting soil types, *J. Environ. Qual.*, 41, 427–435, 2012.

- Philibert, A., Loyce, C., and Makowski, D.: Quantifying uncertainties in N₂O emission due to N fertilizer application in cultivated areas, *PLoS ONE*, 7, e50950, 2012.
- Predotova, M., Schlecht, E., and Buerkert, A.: Nitrogen and carbon losses from dung storage in urban gardens of Niamey, Niger, *Nutr. Cycl. Agroecosys.*, 87, 103–114, 2010.
- Priemé, A. and Christensen, S.: Methane uptake by a selection of soils in Ghana with different land use, *J. Geophys. Res.*, 104, 23617–23622, 1999.
- Rabenarivo, M., Wrage-Moennig, N., Chotte, J. L., Rabeharisoa, L., Razafimbelo, T. M., and Chapuis-Lardy, L.: Emissions of CO₂ and N₂O from a pasture soil from Madagascar-simulating conversion to direct-seeding mulch-based cropping in incubations with organic and inorganic inputs, *J. Plant Nutr. Soil Sci.*, 177, 360–368, 2014.
- Raich, J. and Schlesinger, W.: The global carbon dioxide flux in soil respiration and its relationship to vegetation and climate, *Tellus B*, 44, 81–99, 1992.
- Reed, D. E., Ewers, B. E., and Pendall, E.: Impact of mountain pine beetle induced mortality on forest carbon and water fluxes, *Environ. Res. Lett.*, 9, 105004, doi:10.1088/1748-9326/9/10/105004, 2014.
- Rees, R. M., Wuta, M., Furley, P. A., and Li, C.: Nitrous oxide fluxes from savanna (miombo) woodlands in Zimbabwe, *J. Biogeogr.*, 33, 424–437, 2006.
- Rezaei Rashti, M., Wang, W., Moody, P., Chen, C., and Ghadiri, H.: Fertiliser-induced nitrous oxide emissions from vegetable production in the world and the regulating factors: A review, *Atmos. Environ.*, 112, 225–233, 2015.
- Rochette, P. and Eriksen-Hamel, N. S.: Chamber measurements of soil nitrous oxide flux: Are absolute values reliable?, *Soil Sci. Soc. Am. J.*, 72, 331–342, doi:10.2136/sssaj2007.0215, 2008.
- Rosenstock, T., Rufino, M., Butterbach-Bahl, K., and Wollenberg, E.: Toward a protocol for quantifying the greenhouse gas balance and identifying mitigation options in smallholder farming systems, *Environ. Res. Lett.*, 8, 021003, doi:10.1088/1748-9326/8/2/021003, 2013.
- Rosenstock, T. S., Diaz-Pines, E., Zuazo, P., Jordan, G., Predotova, M., Mutuo, P., Abwanda, S., Thiong'o, M., Buerkert, A., Rufino, M. C., Kiese, R., Neufeldt, H., and Butterbach-Bahl, K.: Accuracy and precision of photoacoustic spectroscopy not guaranteed, *Glob. Change Biol.*, 19, 3565–3567, doi:10.1111/gcb.12332, 2013.
- Rosenstock, T. S., Mathew, M., Pelster, D. E., Butterbach-Bahl, K., Rufino, M. C., Thiong'o, M., Mutuo, P., Abwanda, S., Rioux, J., Kimaro, A. A., and Neufeldt, H. C. J. G.: Greenhouse gas fluxes from agricultural soils of Kenya and Tanzania, *J. Geophys. Res.*, 121, 1568–1580, doi:10.1002/2016JG003341, 2016.
- Saggar, S., Jha, N., Deslippe, J., Bolan, N. S., Luo, J., Giltrap, D. L., Kim, D. G., Zaman, M., and Tillman, R. W.: Denitrification and N₂O:N₂ production in temperate grasslands: Processes, measurements, modelling and mitigating negative impacts, *Sci. Total Environ.*, 465, 173–195, 2013.
- Shcherbak, I., Millar, N., and Robertson, G. P.: Global metaanalysis of the nonlinear response of soil nitrous oxide (N₂O) emissions to fertilizer nitrogen, *P. Natl. Acad. Sci. USA*, 111, 9199–9204, 2014.
- Sheehy, J., Six, J., Alakukku, L., and Regina, K.: Fluxes of nitrous oxide in tilled and no-tilled boreal arable soils, *Agr. Ecosyst. Environ.*, 164, 190–199, 2013.
- Smith, D. L. and Johnson, L.: Vegetation-mediated changes in microclimate reduce soil respiration as woodlands expand into grasslands, *Ecology*, 85, 3348–3361, 2004.
- Smith, K.: Nitrous Oxide and Climate Change, Earthscan, London, UK, 240 pp., 2010.
- Snyder, C. S., Bruulsema, T. W., Jensen, T. L., and Fixen, P. E.: Review of greenhouse gas emissions from crop production systems and fertilizer management effects, *Agr. Ecosyst. Environ.*, 133, 247–266, 2009.
- Sommer, R., Mukalama, J., Kihara, J., Koala, S., Winowiecki, L., and Bossio, D.: Nitrogen dynamics and nitrous oxide emissions in a long-term trial on integrated soil fertility management in western Kenya, *Nutr. Cycl. Agroecosys.*, 105, 229–248, doi:10.1007/s10705-015-9693-6, 2015.
- Stringer, L., Dougill, A. J., Thomas, A. D., Spracklen, D., Chesterman, S., Speranza, C. I., Rueff, H., Riddell, M., Williams, M., and Beedy, T.: Challenges and opportunities in linking carbon sequestration, livelihoods and ecosystem service provision in drylands, *Environ. Sci. Policy*, 19, 121–135, 2012.
- Sugihara, S., Funakawa, S., Kilasara, M., and Kosaki, T.: Effects of land management on CO₂ flux and soil C stock in two Tanzanian croplands with contrasting soil texture, *Soil Biol. Biochem.*, 46, 1–9, 2012.
- Tathy, J., Cros, B., Delmas, R., Marengo, A., Servant, J., and Labat, M.: Methane emission from flooded forest in central Africa, *J. Geophys. Res.*, 97, 6159–6168, 1992.
- Teodoru, C. R., Nyoni, F. C., Borges, A. V., Darchambeau, F., Nyambe, I., and Bouillon, S.: Dynamics of greenhouse gases (CO₂, CH₄, N₂O) along the Zambezi River and major tributaries, and their importance in the riverine carbon budget, *Biogeosciences*, 12, 2431–2453, doi:10.5194/bg-12-2431-2015, 2015.
- Thauer, R.: Biochemistry of methanogenesis: A tribute to marjory stephenson, *Microbiology*, 144, 2377–2406, 1998.
- Thomas, A. D.: Impact of grazing intensity on seasonal variations in soil organic carbon and soil CO₂ efflux in two semiarid grasslands in southern Botswana, *Philos. T. R. Soc. B.*, 367, 3076–3086, 2012.
- Thomas, A. D., Hoon, S. R., and Dougill, A. J.: Soil respiration at five sites along the kalahari transect: Effects of temperature, precipitation pulses and biological soil crust cover, *Geoderma*, 167, 284–294, 2011.
- Thomas, A. D., Dougill, A. J., Elliott, D. R., and Mairs, H.: Seasonal differences in soil CO₂ efflux and carbon storage in Ntwetwet pan, Makgadikgadi Basin, Botswana, *Geoderma*, 219, 72–81, 2014.
- Thompson, R. L., Chevallier, F., Crotwell, A. M., Dutton, G., Langenfelds, R. L., Prinn, R. G., Weiss, R. F., Tohjima, Y., Nakazawa, T., Krummel, P. B., Steele, L. P., Fraser, P., O'Doherty, S., Ishijima, K., and Aoki, S.: Nitrous oxide emissions 1999 to 2009 from a global atmospheric inversion, *Atmos. Chem. Phys.*, 14, 1801–1817, doi:10.5194/acp-14-1801-2014, 2014.
- Tubiello, F. N., Salvatore, M., Rossi, S., Ferrara, A., Fitton, N., and Smith, P.: The FAOSTAT database of greenhouse gas emissions from agriculture, *Environ. Res. Lett.*, 8, 015009, doi:10.1088/1748-9326/8/1/015009, 2013.

- Tubiello, F. N., Salvatore, M., Ferrara, A. F., House, J., Federici, S., Rossi, S., Biancalani, R., Condor Golec, R. D., Jacobs, H., Flammini, A., Prosperi, P., Cardenas-Galindo, P., Schmidhuber, J., Sanz Sanchez, M. J., Srivastava, N., and Smith, P.: The contribution of agriculture, forestry and other land use activities to global warming, 1990–2012, *Glob. Change Biol.*, 21, 2655–2660, 2015.
- Tufekcioglu, A., Raich, J., Isenhardt, T., and Schultz, R.: Soil respiration within riparian buffers and adjacent crop fields, *Plant Soil*, 229, 117–124, 2001.
- Tyler, S. C., Zimmerman, P. R., Cumberbatch, C., Greenberg, J. P., Westberg, C., and Darlington, J. P.: Measurements and interpretation of $\delta^{13}\text{C}$ of methane from termites, rice paddies, and wetlands in Kenya, *Global Biogeochem. Cy.*, 2, 341–355, 1988.
- US EPA: Draft US Greenhouse Gas Inventory Report: 1990–2014, available at: <https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport.html>, last access: 10 April 2016.
- Valentini, R., Arneth, A., Bombelli, A., Castaldi, S., Cazzolla Gatti, R., Chevallier, F., Ciais, P., Grieco, E., Hartmann, J., Henry, M., Houghton, R. A., Jung, M., Kutsch, W. L., Malhi, Y., Mayorga, E., Merbold, L., Murray-Tortarolo, G., Papale, D., Peylin, P., Poulter, B., Raymond, P. A., Santini, M., Sitch, S., Vaglio Laurin, G., van der Werf, G. R., Williams, C. A., and Scholes, R. J.: A full greenhouse gases budget of Africa: synthesis, uncertainties, and vulnerabilities, *Biogeosciences*, 11, 381–407, doi:10.5194/bg-11-381-2014, 2014.
- Van Groenigen, J., Velthof, G., Oenema, O., Van Groenigen, K., and Van Kessel, C.: Towards an agronomic assessment of N_2O emissions: A case study for arable crops, *Eur. J. Soil Sci.*, 61, 903–913, 2010.
- Vargas, R.: How a hurricane disturbance influences extreme CO_2 fluxes and variance in a tropical forest, *Environ. Res. Lett.*, 7, 035704, doi:10.1088/1748-9326/7/3/035704, 2012.
- Verchot, L. V., Brienza Junior, S., de Oliveira, V. C., Mutege, J. K., Cattanio, J. H., and Davidson, E. A.: Fluxes of CH_4 , CO_2 , NO , and N_2O in an improved fallow agroforestry system in eastern Amazonia, *Agr. Ecosyst. Environ.*, 126, 113–121, 2008.
- Wang, Z. A., Bienvenu, D. J., Mann, P. J., Hoering, K. A., Poulsen, J. R., Spencer, R. G., and Holmes, R. M.: Inorganic carbon speciation and fluxes in the Congo River, *Geophys. Res. Lett.*, 40, 511–516, 2013.
- Werner, C., Kiese, R., and Butterbach-Bahl, K.: Soil-atmosphere exchange of N_2O , CH_4 , and CO_2 and controlling environmental factors for tropical rain forest sites in western Kenya, *J. Geophys. Res.*, 112, D03308, doi:10.1029/2006JD007388, 2007.
- Wrage, N., Velthof, G. L., van Beusichem, M. L., and Oenema, O.: Role of nitrifier denitrification in the production of nitrous oxide, *Soil Biol. Biochem.*, 33, 1723–1732, 2001.
- Yang, J., Liu, J., Hu, X., Li, X., Wang, Y., and Li, H.: Effect of water table level on CO_2 , CH_4 and N_2O emissions in a freshwater marsh of Northeast China, *Soil Biol. Biochem.*, 61, 52–60, 2013.
- Yashiro, Y., Kadir, W. R., Okuda, T., and Koizumi, H.: The effects of logging on soil greenhouse gas (CO_2 , CH_4 , N_2O) flux in a tropical rain forest, Peninsular Malaysia, *Agr. Forest. Meteorol.*, 148, 799–806, 2008.
- Yohannes, Y., Shibistova, O., Abate, A., Fetene, M., and Guggenberger, G.: Soil CO_2 efflux in an afro-montane forest of Ethiopia as driven by seasonality and tree species, *Forest Ecol. Manage.*, 261, 1090–1098, doi:10.4172/2168-9776.1000111, 2011.
- Yohannes, Y., Shibistova, O., Asaye, Z., and Guggenberger, G.: Forest management influence on the carbon flux of cupressus lusitanica plantation in the Munessa forest, Ethiopia, *Forest Res.*, 2, 111, doi:10.4172/2168-9776.1000111, 2013.
- Zepp, R. G., Miller, W. L., Burke, R. A., Parsons, D. A. B., and Scholes, M. C.: Effects of moisture and burning on soil-atmosphere exchange of trace carbon gases in a southern African savanna, *J. Geophys. Res.*, 101, 23699–23706, 1996.
- Zomer, R. J., Trabucco, A., Coe, R., and Place, F.: Trees on farm: analysis of global extent and geographical patterns of agroforestry, ICRAF Working Paper No. 89, (World Agroforestry Centre (ICRAF), 2009), <http://www.worldagroforestry.org/downloads/Publications/PDFs/WP16263.PDF>, last access: 18 August 2016.